Experimental Physics at the Large Hadron Collider

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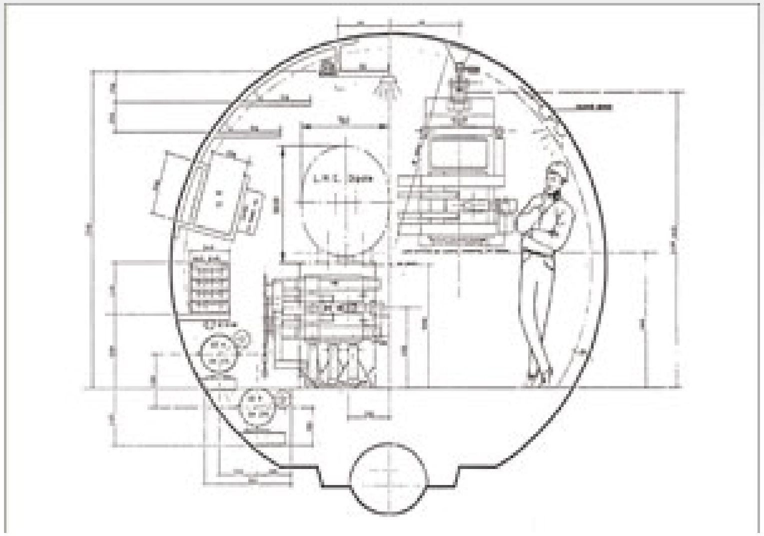
Outline

- The machine: why the LHC is a unique collider
- Characteristics of ATLAS and CMS
- Parton density functions and luminosity
- QCD physics
- Production of vector bosons and top
- Higgs boson
- Search for physics beyond SM

A bit of history...

In the eighties, CERN built LEP, the large electron-positron collider, in a 26.6 km tunnel at average depth of 100m.

It was the largest civil-engineering project in Europe at that time.



Already in spring 1984 (5 years before LEP started operations!) a workshop was held on the possibility of building ”a Large Hadron Collider” in the LEP tunnel

Towards the LHC

At that time, the US was building a very ambitious hadron collider, the SSC in Texas.

In 1993 the US congress canceled the SSC project due to budget cuts, the LHC was the only viable project for the energy frontier (and approved in 1994)

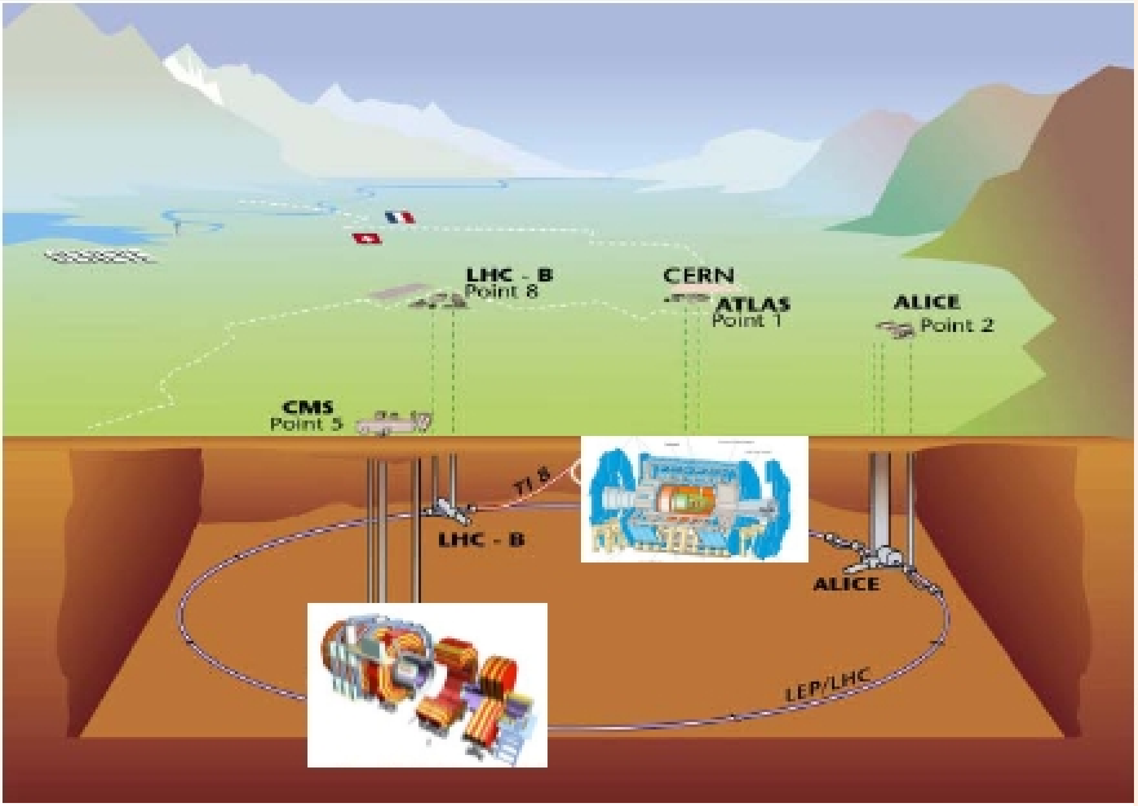
...maybe not so bad for our health...

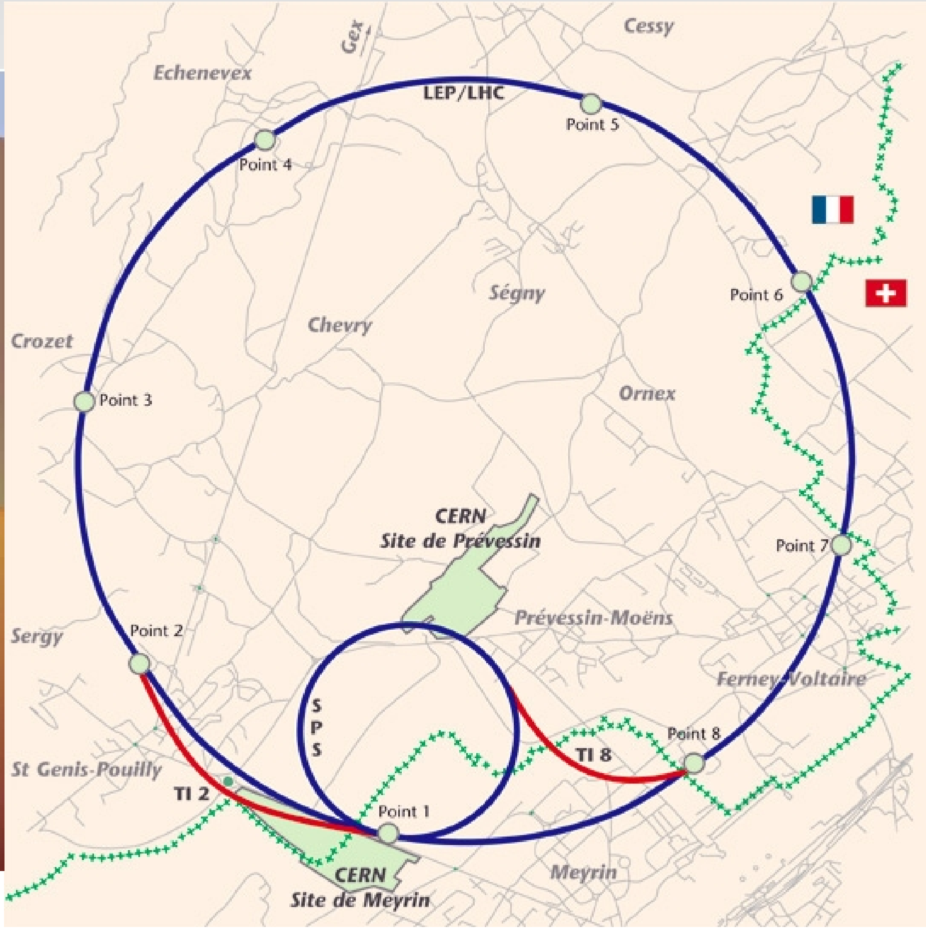
The discussion on detectors was well under way, and after many merges ATLAS and CMS were approved in 1995

What LHC does not stand for (non part of the lecture ;-)

This is of course a joke... but this image (of a rock band of Cern secretaries active in the first 90es) was THE FIRST IMAGE EVER ON THE WEB

LHC layout


LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
TI 8
LHC - B
ALICE
LEP/LHC


Cessy
Gex
Echenevex
LEP/LHC
Point 5
Point 4
Crozet
Point 3
Chevry
Ségny
Point 6
Ornex
CERN
Site de Prévessin
Point 7
Prévessin-Moëns
Sergy
Point 2
Ferney-Voltaire
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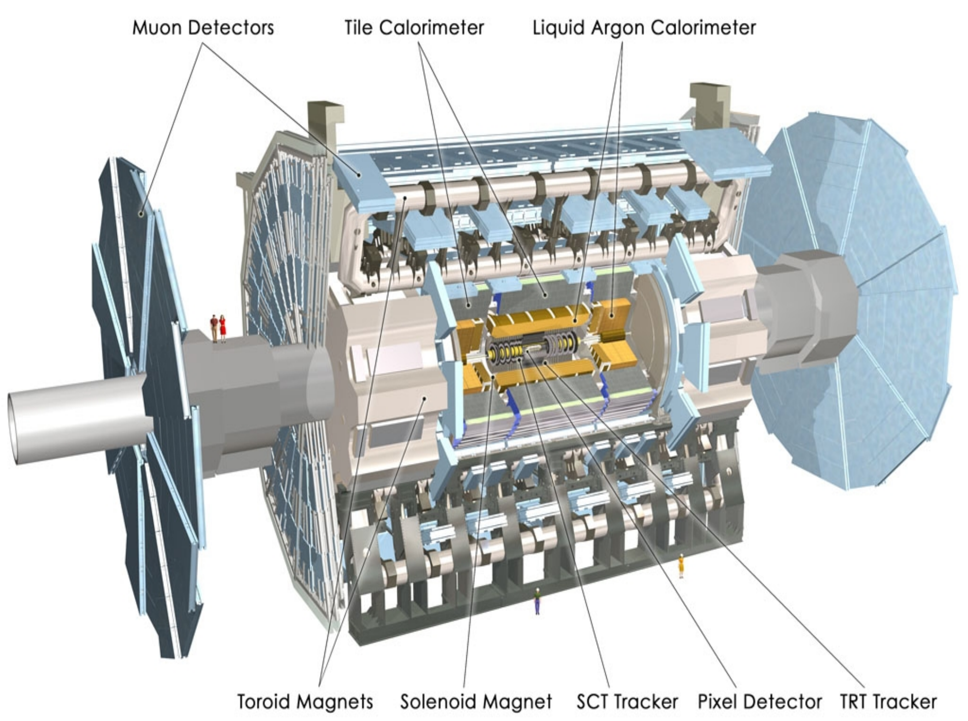
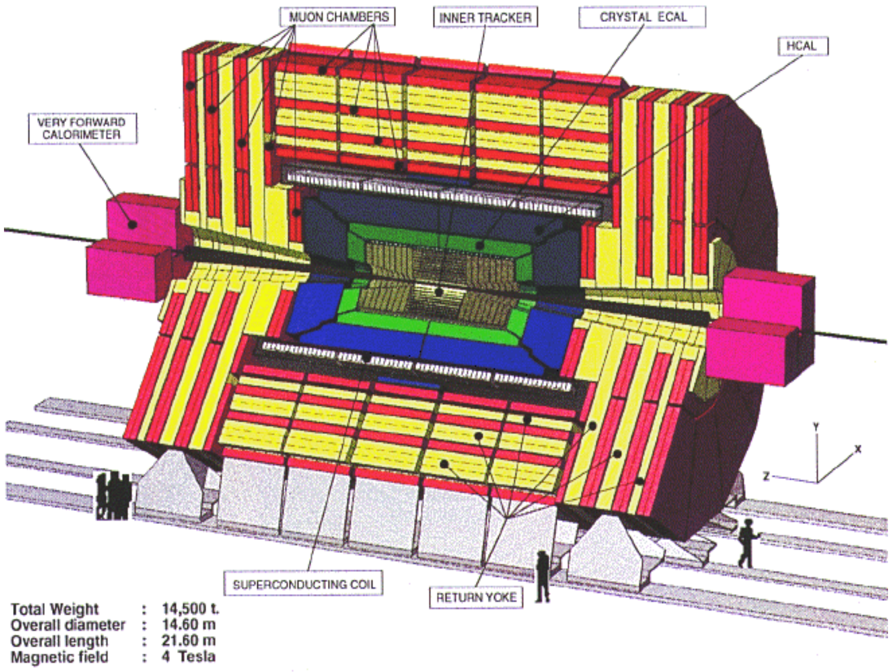
Point 8
TI 8
St Genis-Pouilly
TI 2
Point 1
CERN
Site de Meyrin
Meyrin

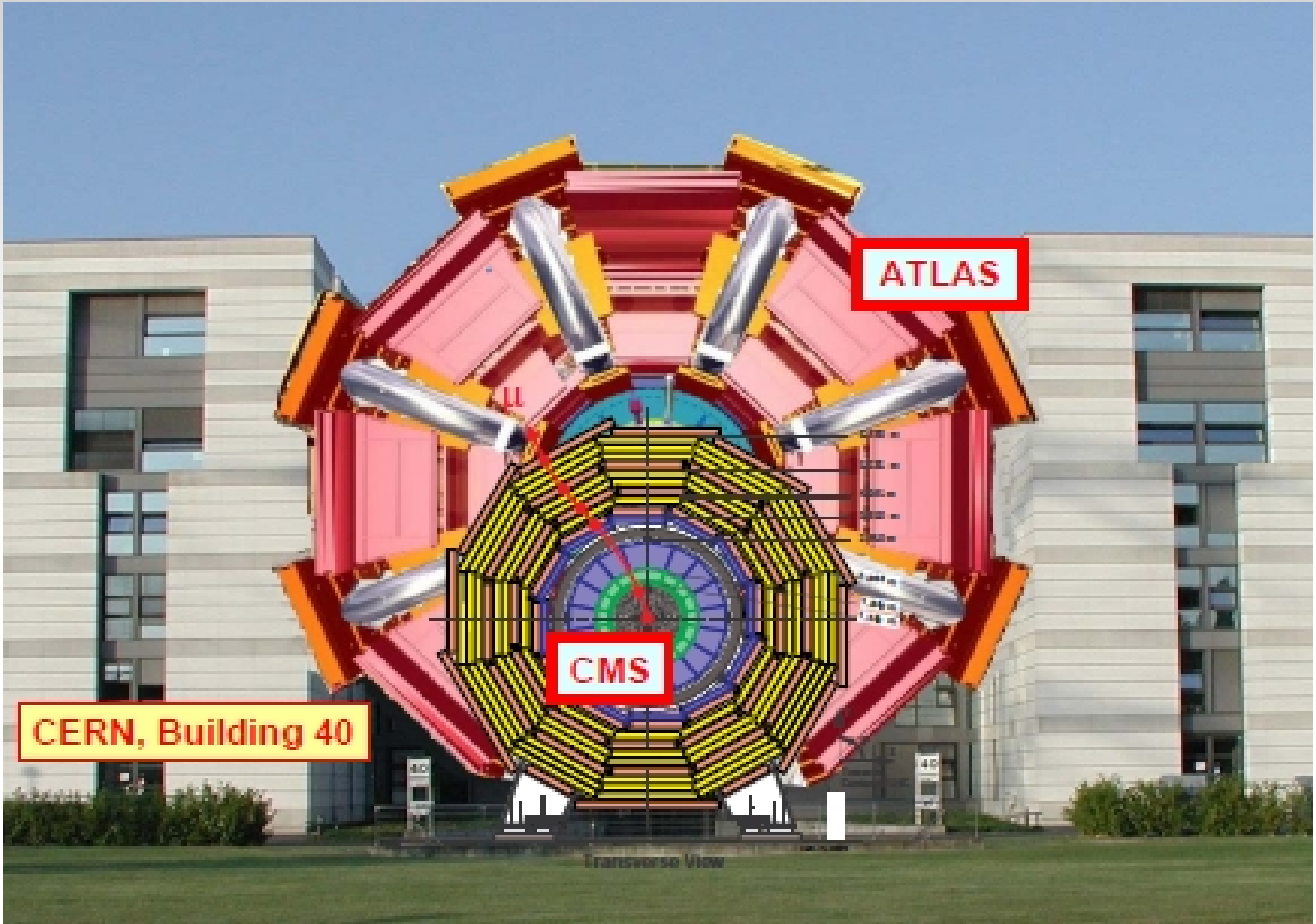
Two general-purpose detectors



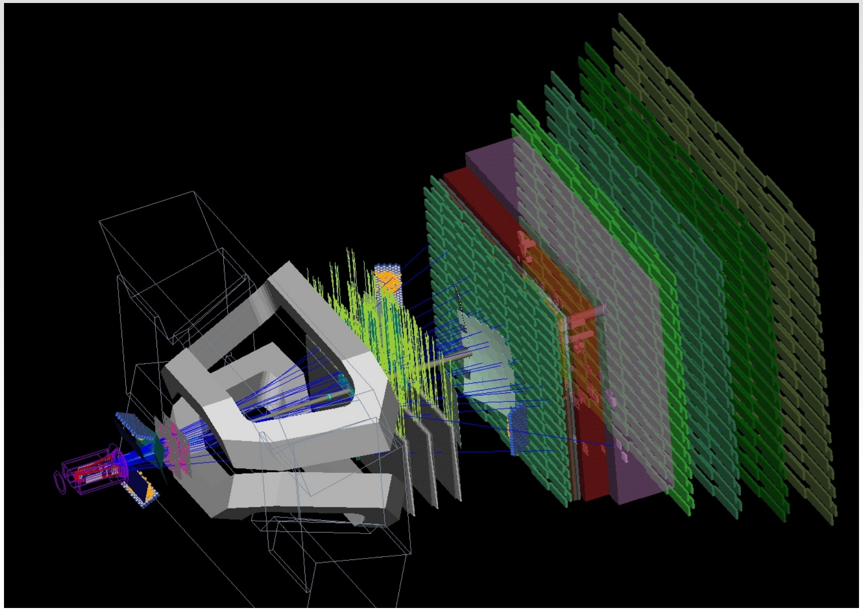


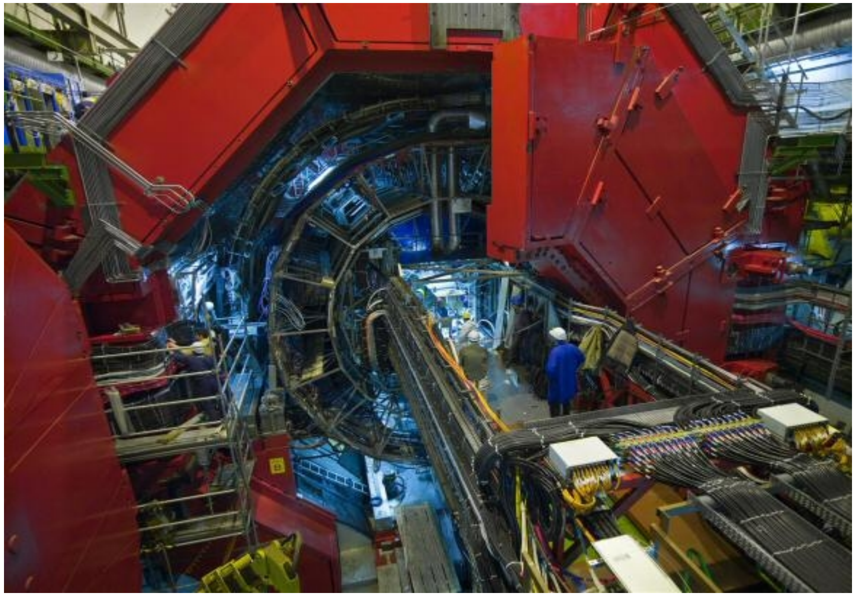
- Atlas: 1 solenoid (2T) and 8 + 2 toroid magnets (!)
  - Air-core muon chambers (good stand-alone muons)
  - Liquid Argon e.m. Calorimeter
- CMS: 1 solenoid magnet (4T) creates field inside and outside
  - Muon chambers in return yoke
  - 80000 $PbWO_4$ crystals as e.m. calorimeter

Why CMS stands for 'compact'



Two dedicated 'low-rate' experiments (not covered)



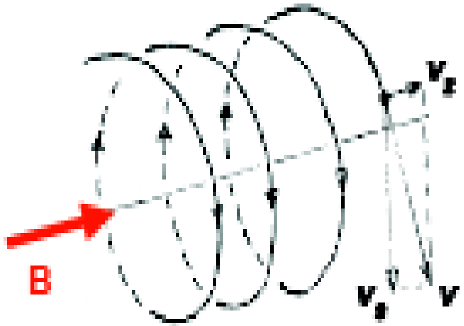


LHCb dedicated to forward low-andgle physics (especially b-quark production) looks like a pyramid with axis on the beam

Very good particle identification

Alice looks for high-mutiplicity events in nucleus-nucleus collisions- the only LHC detector to have a gas tracker due to low-lumi and high-occupancy operation

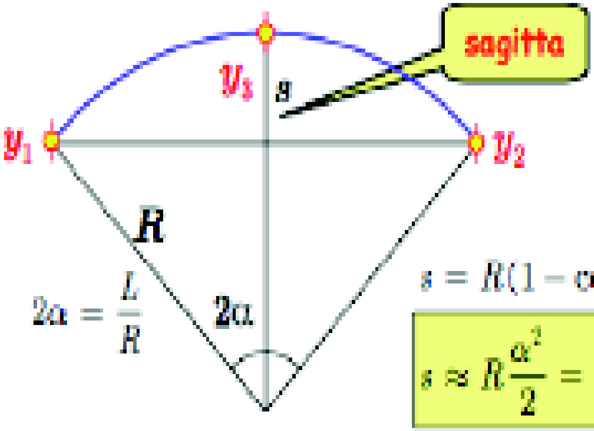
Measuring momentum



$$\boxed{R(m) = \frac{p_\perp(GeV)}{0.3B(T)}}$$

Since the transverse momentum is proportional to the bending radius, the momen resolution depend on the accuracy in measuring R

$$\boxed{R = \frac{p}{0.3B} \qquad \frac{\delta p}{p} = \frac{\delta R}{R}}$$



$$2\alpha = \frac{L}{R}$$

$$s = y_3 - \frac{y_1 + y_2}{2} \qquad \delta s = \sqrt{\frac{3}{2}}\delta y \sim \delta y$$

$$s = R(1 - \cos\alpha)$$

$$\boxed{s \approx R\frac{\alpha^2}{2} = \frac{L^2}{8R}}$$

$$|\delta s| = \frac{L^2}{8R}\frac{\delta R}{R} \sim \delta y \qquad \frac{L^2}{8R}\frac{\delta p}{p} = \delta y$$

$$\frac{\delta p}{p} = \frac{8R}{L^2}\delta y \qquad \frac{\delta p}{p} = \frac{8p}{0.3BL^2}\delta y$$

$$\boxed{\frac{\delta p}{p^2} = \frac{8\delta y}{0.3BL^2}}$$

Atlas tracker

Pixel Detector

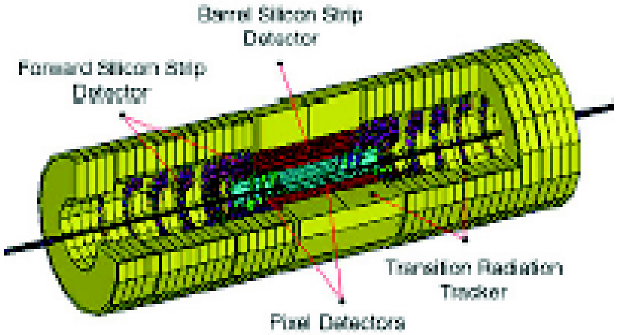
- 3 barrels, 3+3 disks: 80×10^6 pixels
- barrel radii: 4.7, 10.5, 13.5 cm
- pixel size 50×400 μm
- s_{rf}= 6-10 μm s_z = 66 μm

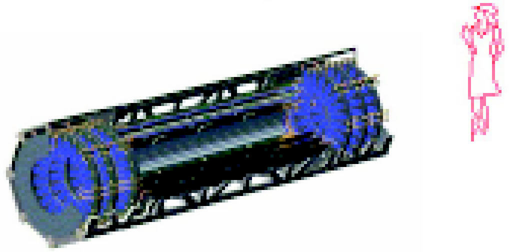
SCT

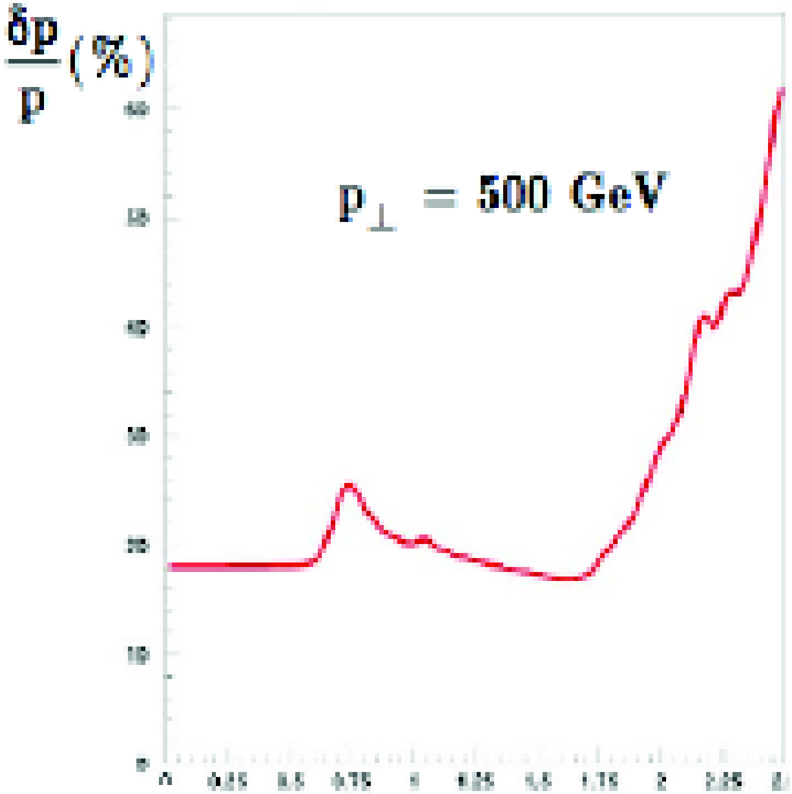
- 4 barrels, disks: 6.3×10^6 strips
- barrel radii:30, 37, 44 ,51 cm
- strip pitch 80 μm
- stereo angle ~40 mr
- s_{rf}= 16 μm s_z = 580μm

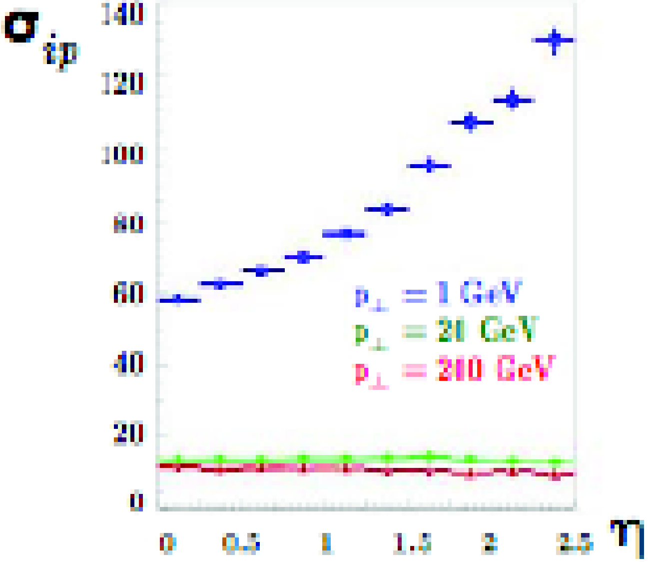
TRT

- barrel: 55 cm < R < 105 cm
- 36 layers of straw tubes
- s_{rf}= 170 μm
- 400.000 channels









CMS tracker

Pixel Detector

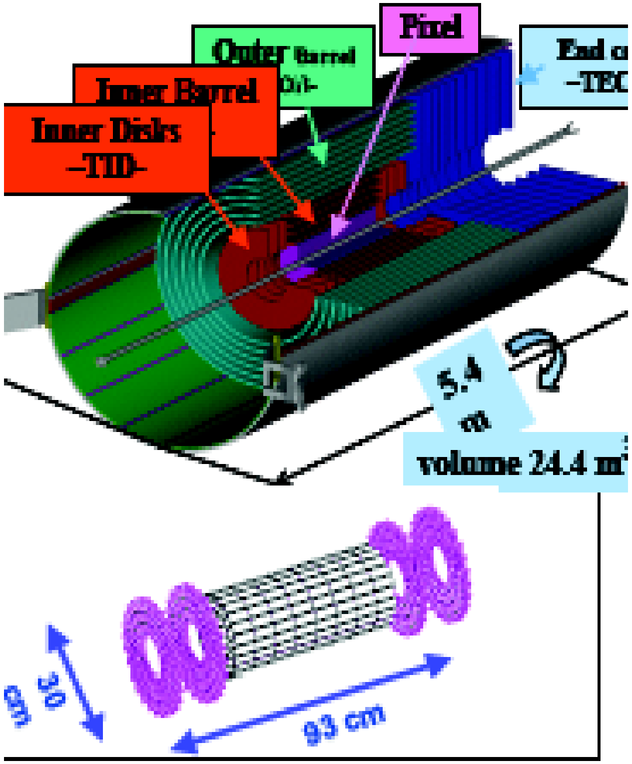
- 2 barrels, 2 disks: 40x10⁶ pixels
- barrel radii: 4.1, ~10. cm
- pixel size 100x150 μm
- $\sigma_{r\phi}$= 10 μm σ_z = 10 μm

Internal Silicon Strip Tracker

- 4 barrels, many disks: 2x10⁶ strips
- barrel radii:
- strip pitch 80,120 μm
- $\sigma_{r\phi}$= 20 μm σ_z = 20 μm

External Silicon Strip Tracker

- 6 barrels, many disks: 8x10⁶ strips
- barrel radii: max 110 cm
- strip pitch 80, 120 μm
- $\sigma_{r\phi}$= 30 μm σ_z = 30 μm



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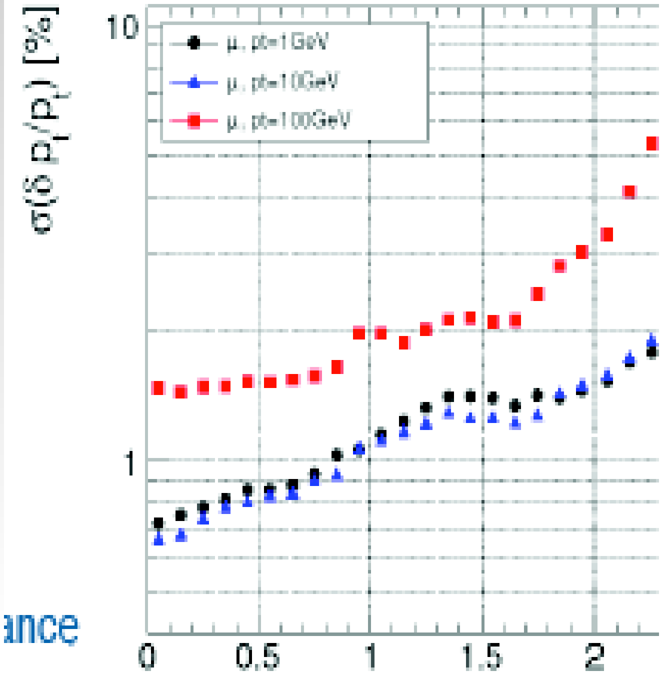
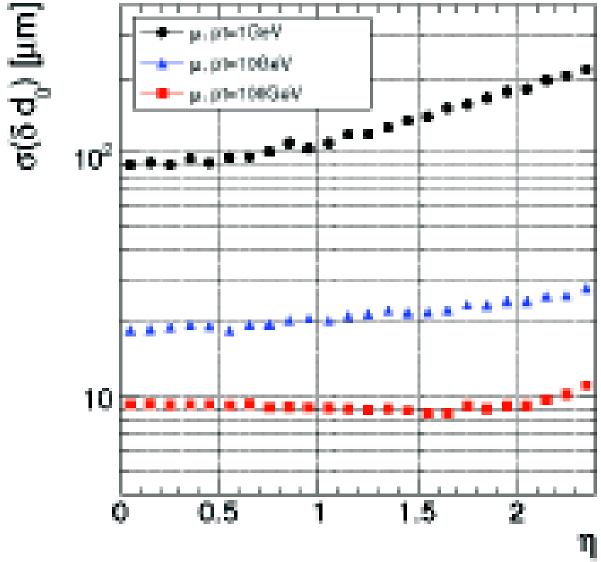
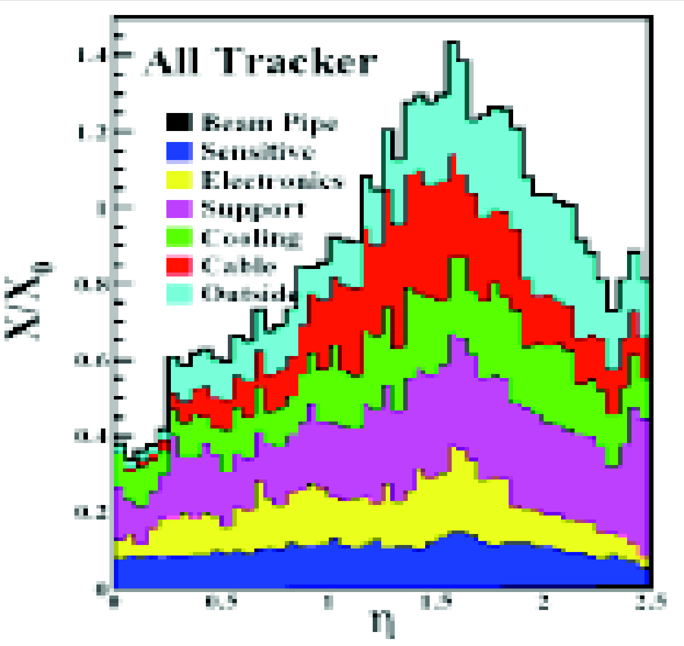
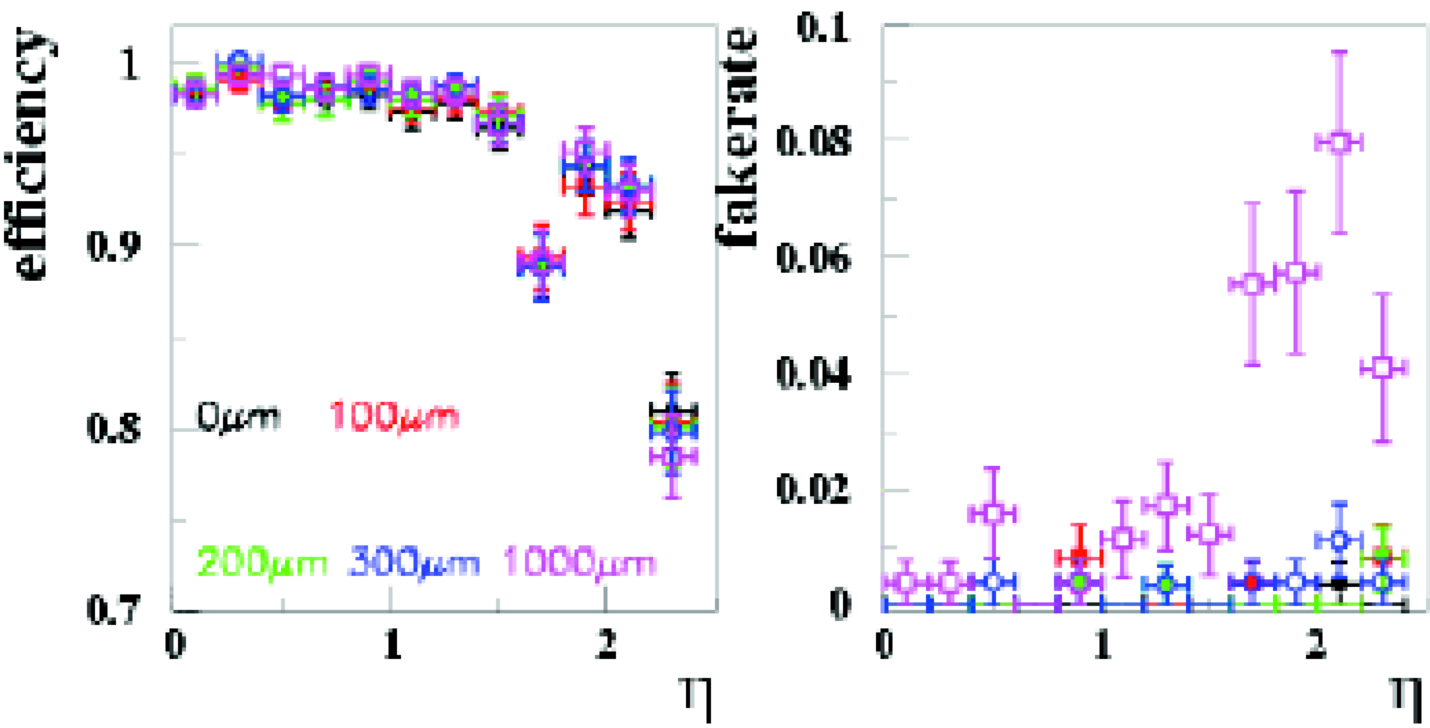




Issues: material budget and alignment

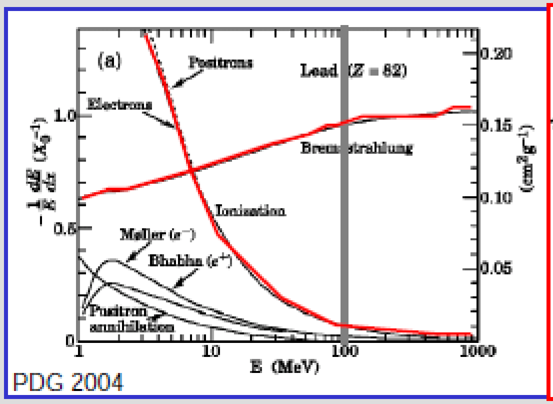


Detector should be thick enough to collect enough signal, and thin enough to minimise photon conversions. Also overlap between modules needed for alignment (starts to be critical at the mm level)



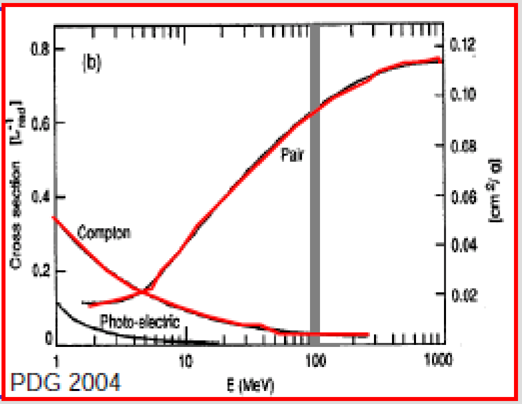
Interactions of electrons and photons in a calorimeter

Electrons and Positrons



PDG 2004

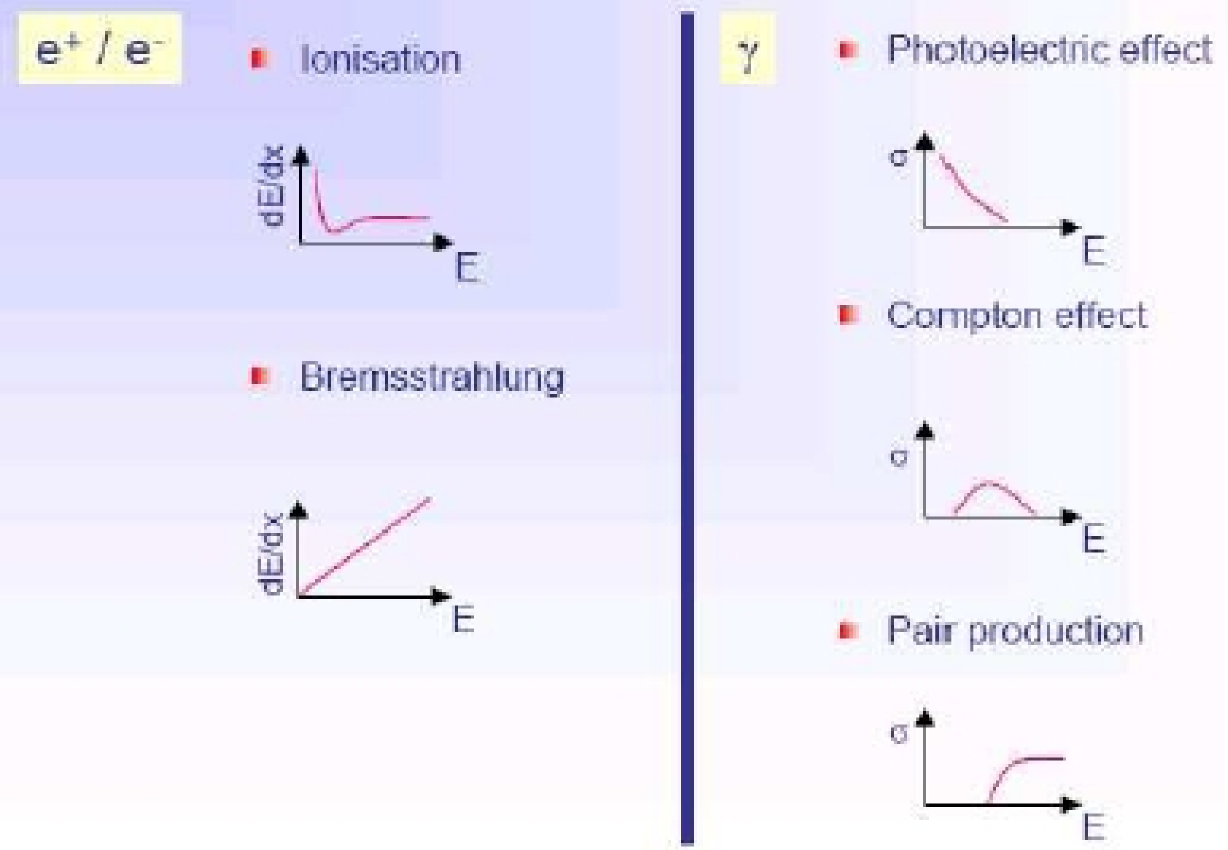
Photon



PDG 2004

Electromagnetic showers occur earlier and are shorter than hadronic ones. Also detector resolution can be very good

Electron- or photon-initiated showers almost impossible to distinguish without preshower detector in front of calorimeter, despite very different interaction properties



e^+ / e^-

- Ionisation

- Bremsstrahlung

γ

- Photoelectric effect

- Compton effect

- Pair production

Calorimeter performance for invariant mass reconstruction

Natural width: for $M_H \approx 100$ GeV $\rightarrow \Gamma_H / M_H \leq 10^{-3}$

Experimental width of $m\gamma\gamma = 2\,E_1\,E_2\,(1 - \cos\theta_{\gamma\gamma})$:

$$\frac{\sigma_m}{m} = \frac{1}{\sqrt{2}}\left[\left(\frac{\sigma_1}{E_1}\right) \oplus \left(\frac{\sigma_2}{E_2}\right) \oplus \left(\frac{\sigma_\theta}{tg\theta_{\gamma\gamma}/2}\right)\right]$$

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

$$\sigma(\theta) \approx \frac{50\ \mathrm{mrad}}{\sqrt{\mathrm{E}}}$$

Same for ATLAS and CMS …

ATLAS-CMS comparison

CMS

- Compact
- Excellent energy resolution
- Fast
- High granularity
- Radiation resistance
- E range MIP → TeV

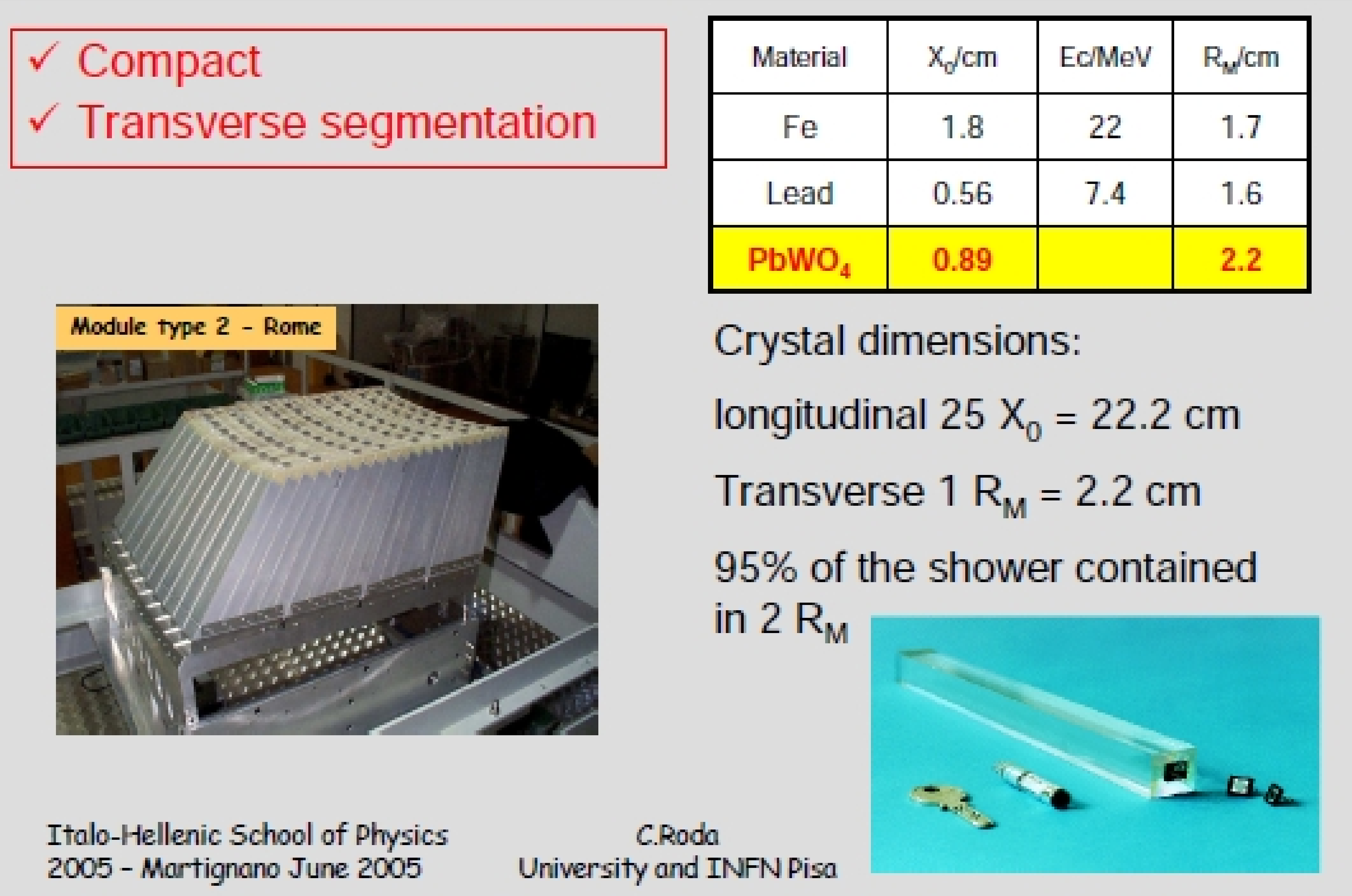
Homogeneous calorimeter made of 75000 $\mathrm{PbW0_4}$ scintillating crystals

ATLAS

- good energy resolution
- Fast
- High granularity
- Longitudinally segmented
- Radiation resistance
- E range MIP → TeV

Sampling LAr-Pb, 3 Longitudinal layers + PS

CMS crystal calorimeter



- ✓ Compact
- ✓ Transverse segmentation

Material	X_0/cm	Ec/MeV	R_M/cm
Fe	1.8	22	1.7
Lead	0.56	7.4	1.6
$PbWO_4$	**0.89**		**2.2**

Module type 2 - Rome

Crystal dimensions:

longitudinal 25 X_0 = 22.2 cm

Transverse 1 R_M = 2.2 cm

95% of the shower contained in 2 R_M

The ATLAS LAr calorimeter

- Longitudinal dimension:

≈25 X_0 = 47 cm (CMS 22 cm)

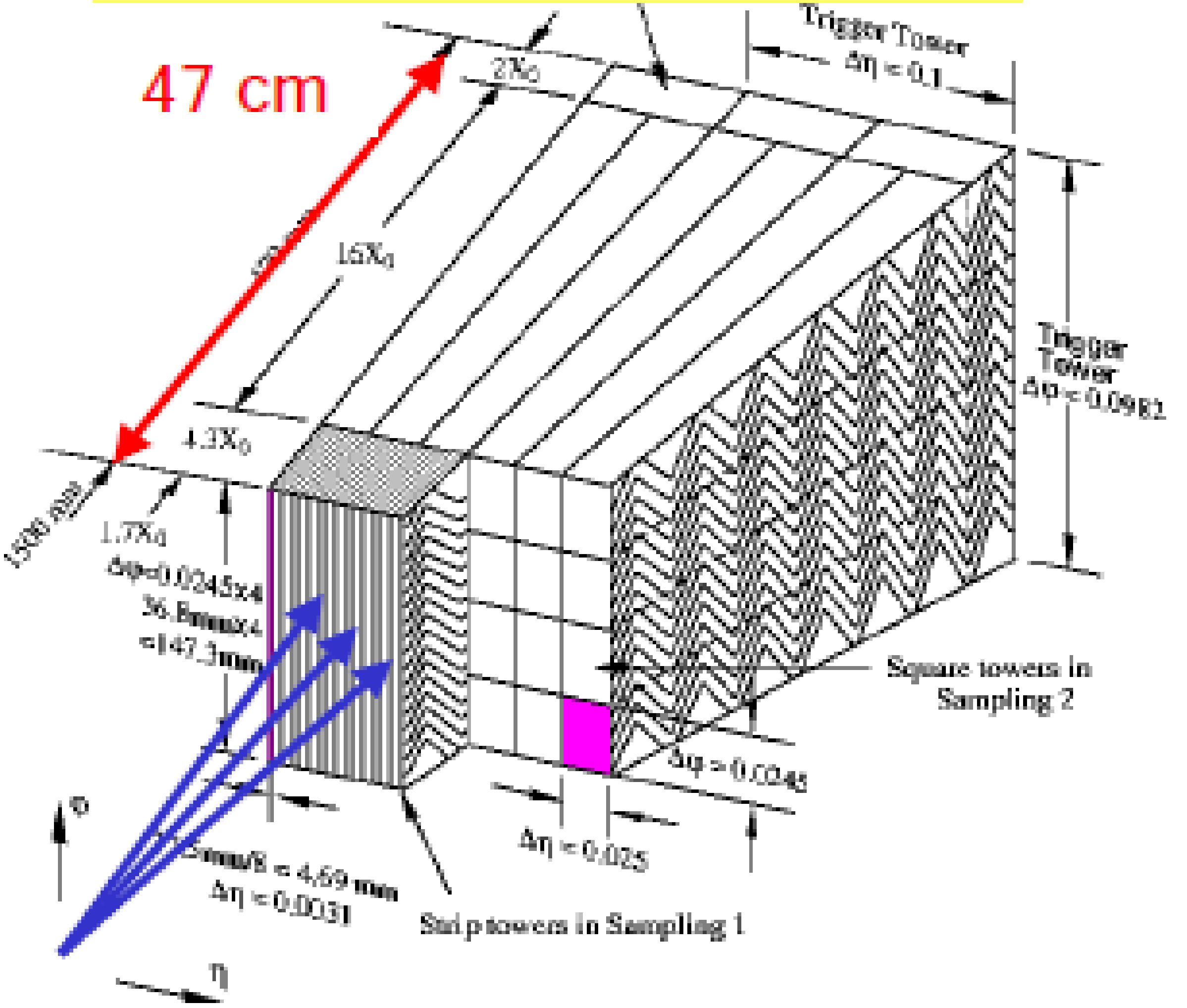
- 3 longitudinal layers

4 X_0 π^0 rejections separation of 2 photons very fine grain in η

16 X_0 for shower core

2 X_0 evaluation of late started showers

- Total channels = 170000

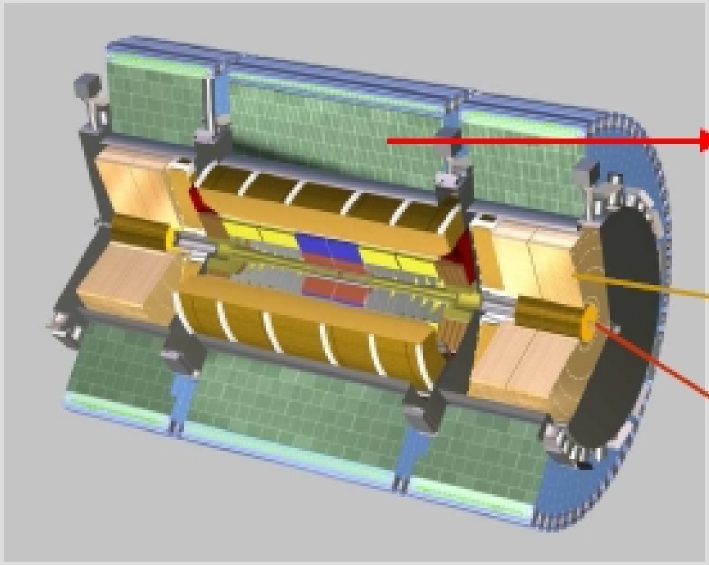


Sampling: accordion lead structure filled with LAr

47 cm

Particles from collisions

Hadronic calorimetry

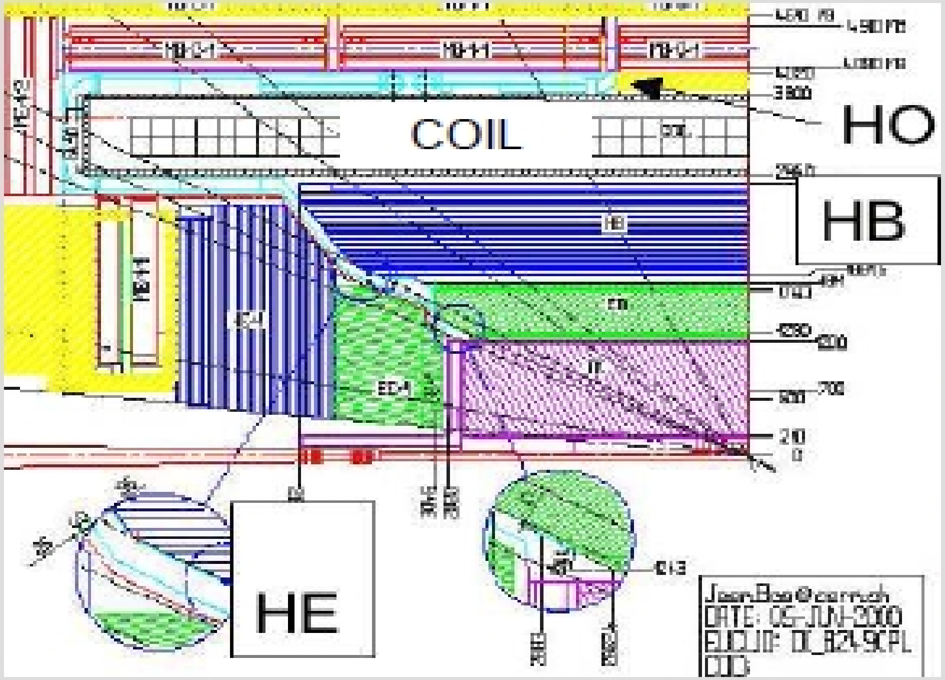


Tile Calorimeter $|\eta| < 1.7$
Fe / Scintillator
3 longitudinal sections

LAr/Cu $1.7 < |\eta| < 3.2$
4 longitudinal sections

Both hadronic and em
LAr/Cu or W $3.2 < |\eta| < 4.9$
3 longitudinal sections

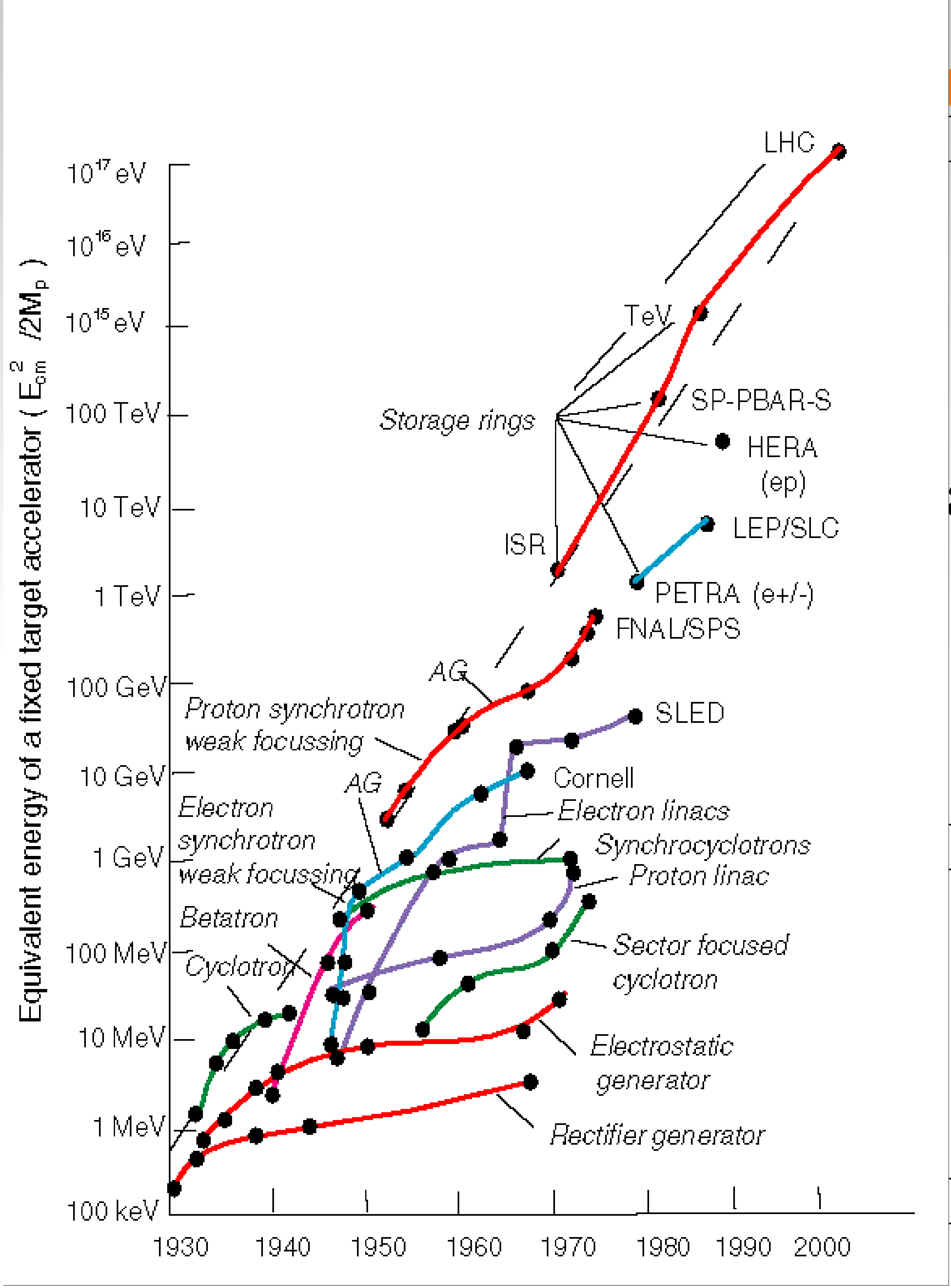
Fluctuations in hadronic showers pose an intrinsic limit to the resolution of hadron calorimetry; this (and the size) is why usually HCALs are less sophisticated then ECALs



Central Hadronic $|\eta| < 1.7$:
Brass/Scintillator + WLS
2 + 1 (HO) Longitudinal section
$5.9 + 3.9\ \lambda$ ($|\eta| = 0$)
Endcap Hadronic $1.3 < |\eta| < 3$:
Brass/Scintillator + WLS
2/3 Longitudinal sections

Forward calorimeter $2.85 < \eta < 5.19$:
Ferro/fibre di quarzo

er?



Lepton colliders provide cleaner events, and all energy is available in the final state. But:

a hadron collider is not limited by synchrotron radiation, and can go to much higher energy.

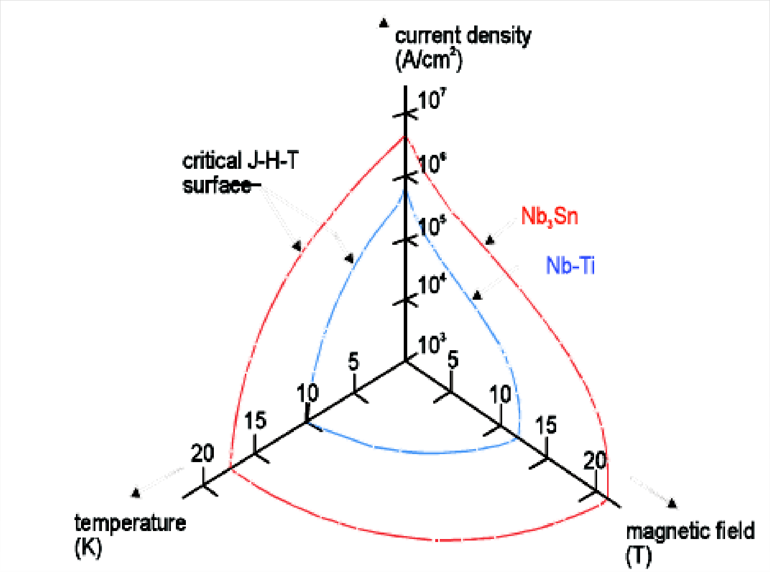
For a given ring size, the only limitation comes from the magnetic field of the bending magnets:

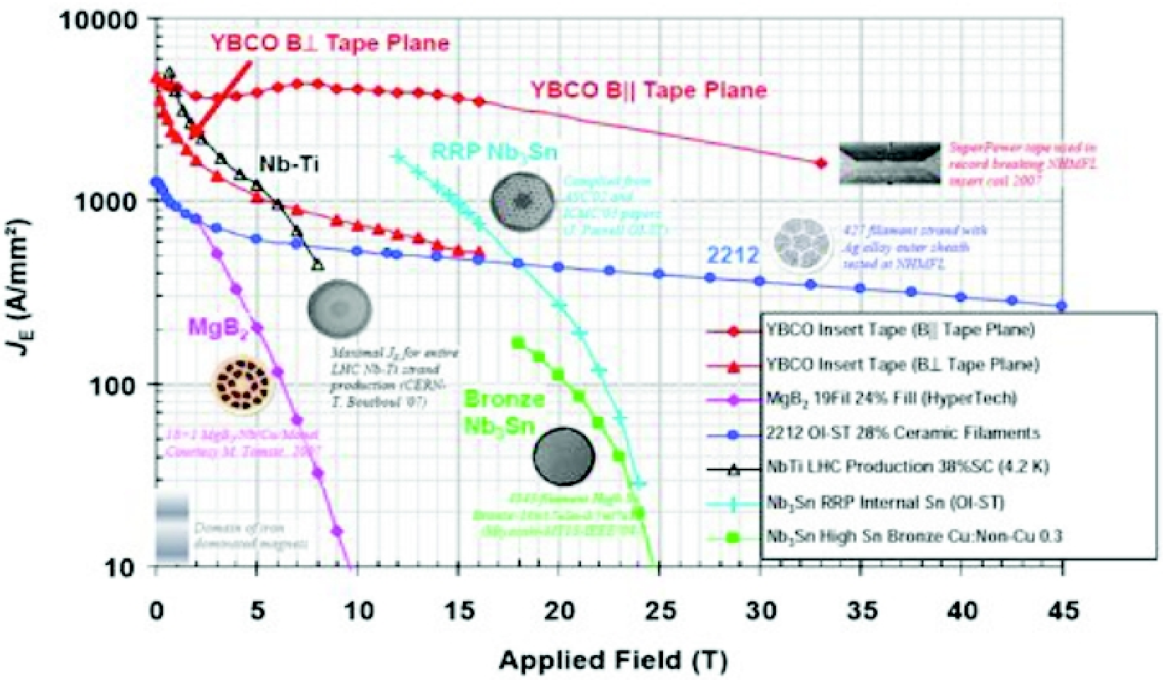
$P\,(\mathrm{TeV}) = 0.3\,B(\mathrm{T})\,R\,(\mathrm{Km})$

Limitation to magnetic field

The highest currents, therefore the largest fields, are obtained using superconducting cables.

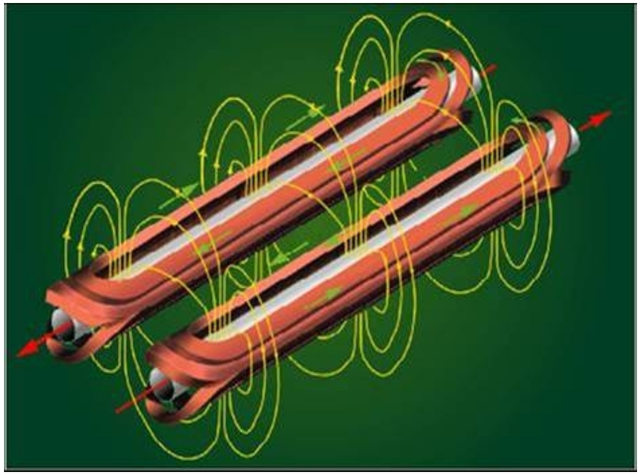
Unfortunately, phase transition between super-and normal conducting phase depends not only on temperature but on magnetic fields. This sets maximum field to 8.4T (100K times earth!) and defines P = 14 TeV (60% of circumference has magnets)

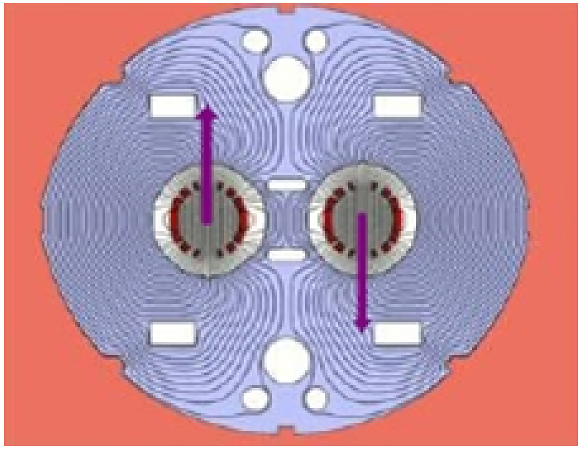




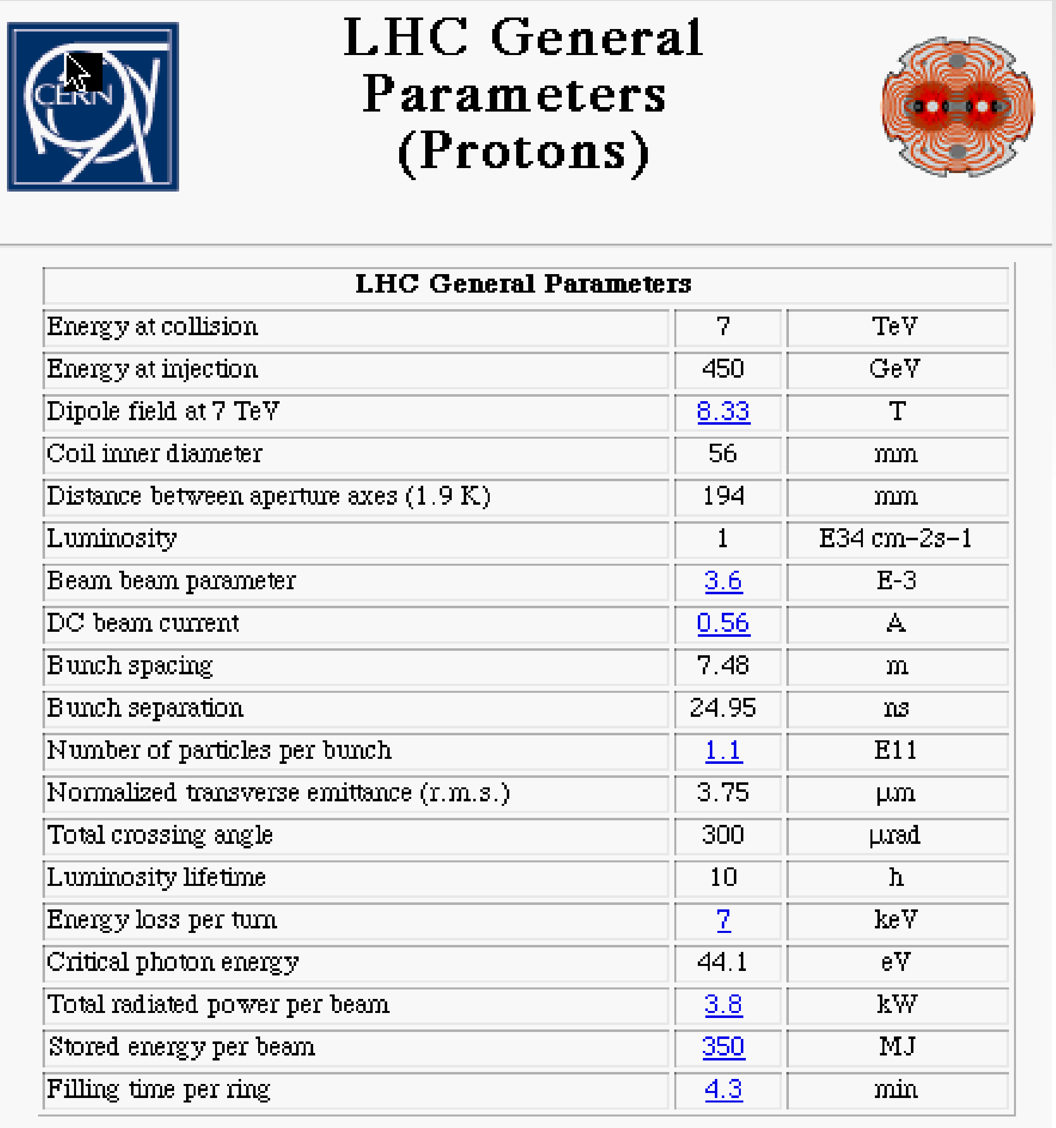
2-in-1 configuration

- Unlike LEP or the Tevatron, the LHC is a proton-proton (matter-matter) machine
- Why? Not possible to produce enough antiprotons to have the large luminosities needed for rare processes
- Most of interactions will be gluon-gluon (see later)
- Technical difficulty: get a very accurately opposite magnetic field



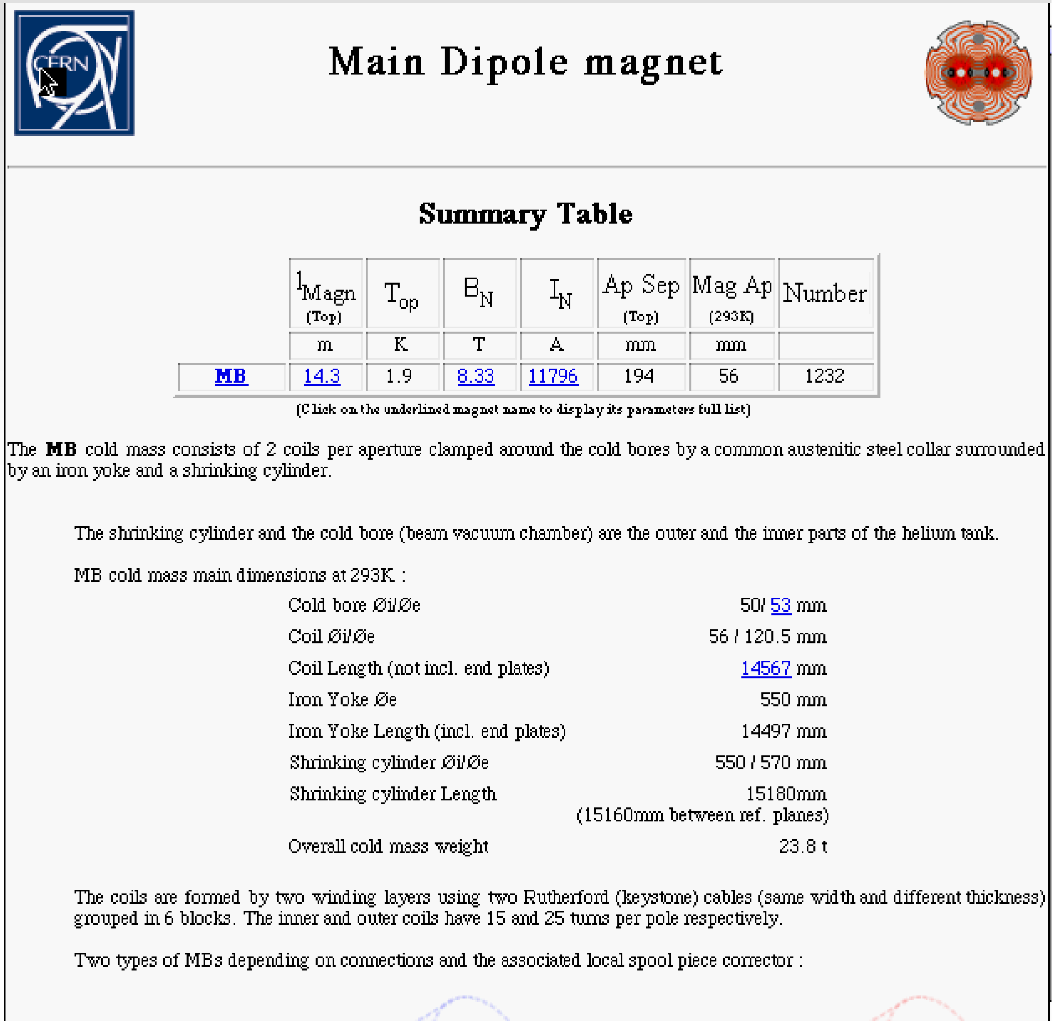


Some parameters



LHC General Parameters (Protons)

LHC General Parameters		
Energy at collision	7	TeV
Energy at injection	450	GeV
Dipole field at 7 TeV	8.33	T
Coil inner diameter	56	mm
Distance between aperture axes (1.9 K)	194	mm
Luminosity	1	E34 cm-2s-1
Beam beam parameter	3.6	E-3
DC beam current	0.56	A
Bunch spacing	7.48	m
Bunch separation	24.95	ns
Number of particles per bunch	1.1	E11
Normalized transverse emittance (r.m.s.)	3.75	µm
Total crossing angle	300	µrad
Luminosity lifetime	10	h
Energy loss per turn	7	keV
Critical photon energy	44.1	eV
Total radiated power per beam	3.8	kW
Stored energy per beam	350	MJ
Filling time per ring	4.3	min



Main Dipole magnet

Summary Table

	l_{Magn} (Top)	T_{op}	B_N	I_N	Ap Sep (Top)	Mag Ap (293K)	Number
	m	K	T	A	mm	mm	
MB	14.3	1.9	8.33	11796	194	56	1232

(Click on the underlined magnet name to display its parameters full list)

The **MB** cold mass consists of 2 coils per aperture clamped around the cold bores by a common austenitic steel collar surrounded by an iron yoke and a shrinking cylinder.

The shrinking cylinder and the cold bore (beam vacuum chamber) are the outer and the inner parts of the helium tank.

MB cold mass main dimensions at 293K :

Cold bore Øi/Øe	50/ 53 mm
Coil Øi/Øe	56 / 120.5 mm
Coil Length (not incl. end plates)	14567 mm
Iron Yoke Øe	550 mm
Iron Yoke Length (incl. end plates)	14497 mm
Shrinking cylinder Øi/Øe	550 / 570 mm
Shrinking cylinder Length	15180mm (15160mm between ref. planes)
Overall cold mass weight	23.8 t

The coils are formed by two winding layers using two Rutherford (keystone) cables (same width and different thickness) grouped in 6 blocks. The inner and outer coils have 15 and 25 turns per pole respectively.

Two types of MBs depending on connections and the associated local spool piece corrector :

Event rate and luminosity

- Rate: number of collisions/s for a given process:
    - $R = \sigma L$

where luminosity L is given by

- $L = f\, n_1 n_2 / A$

- $n_1 n_2$ number of particles per beam ($O(10^{11})$)
- f crossing frequency (40 Mhz, with 2835/3564 bunches occupied)
- A = crossing area = πr^2 where $r = 16\ \mu m$ (rms of transverse beam profile)

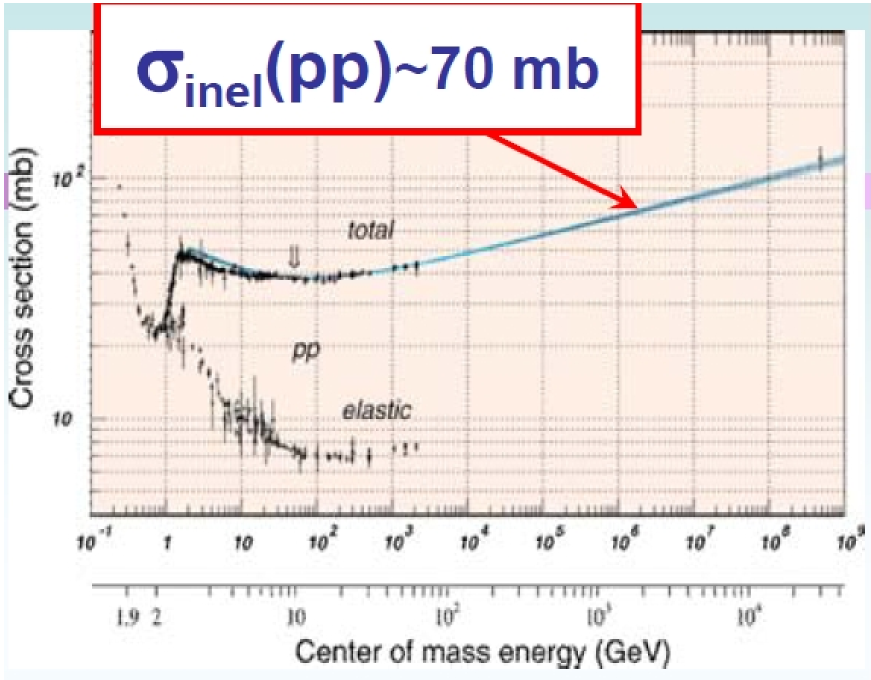
Integrated luminosity and pileup

- These numbers correspond to a range between

10^{33} and 10^{34} cm^2/s (10^6-10^7 mb^{-1}) Hz

And in one year (8-9 months of data taking) to 10-100 fb^{-1}

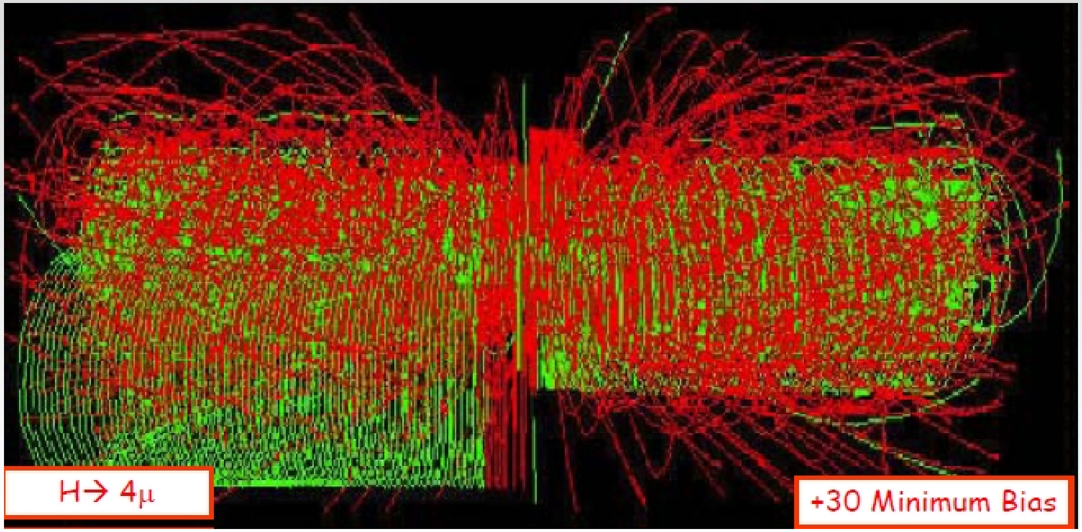
The total pp cross section is about 70 mb:



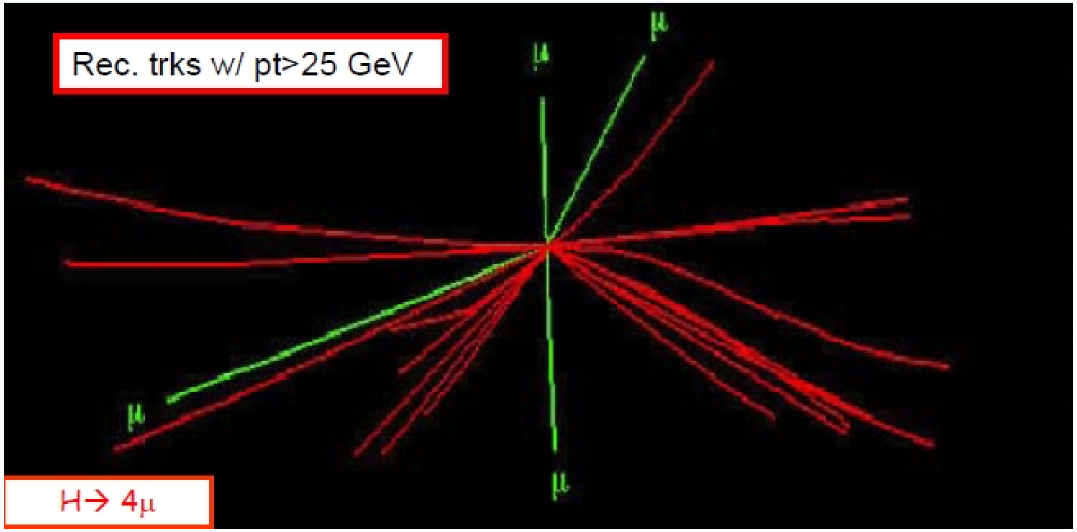
So, rate can go up to 700MHz! Divided by 40MHz bunch crossing rate, and accounting for empty bunches, we can have > 20 collisions/bunch crossing (pileup)

Pileup

Can you find four muons coming from a Higgs boson from this event?

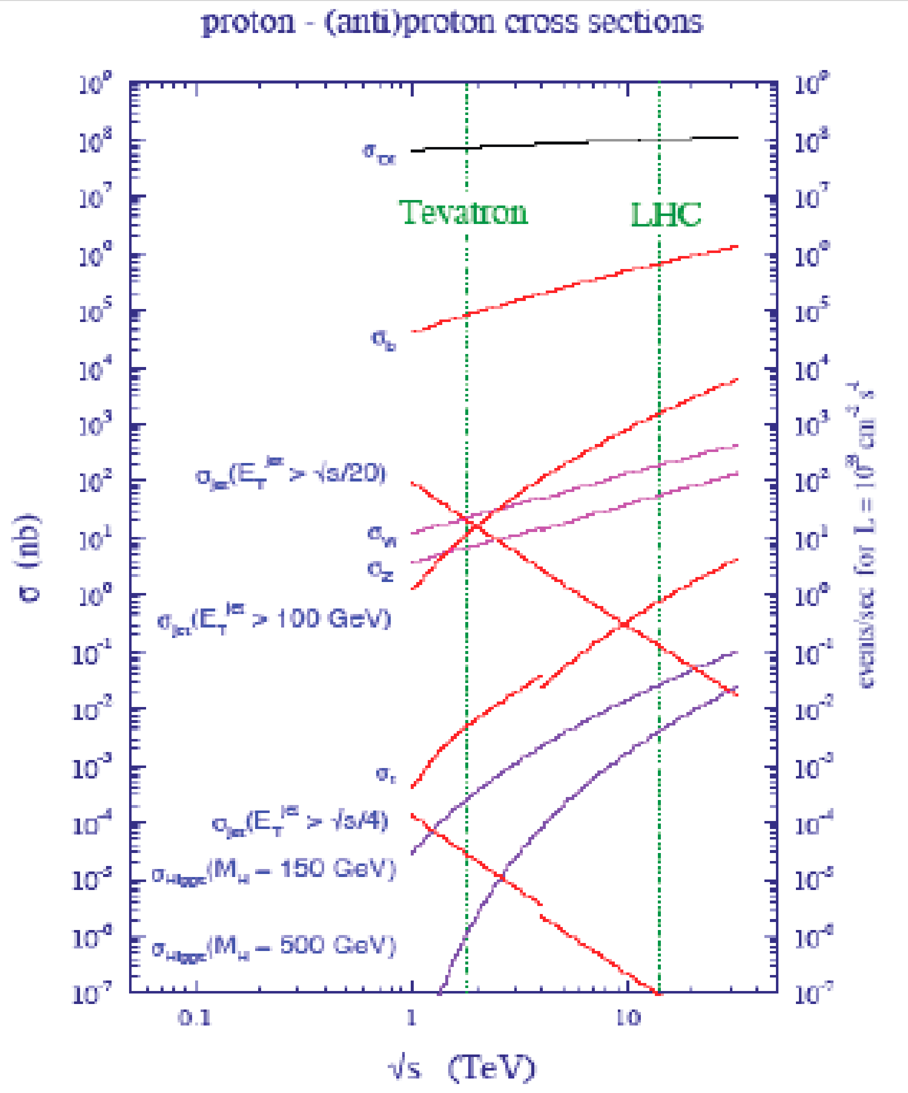


It gets much better if you just look at the energetic particles:



Cross sections in pp interactions

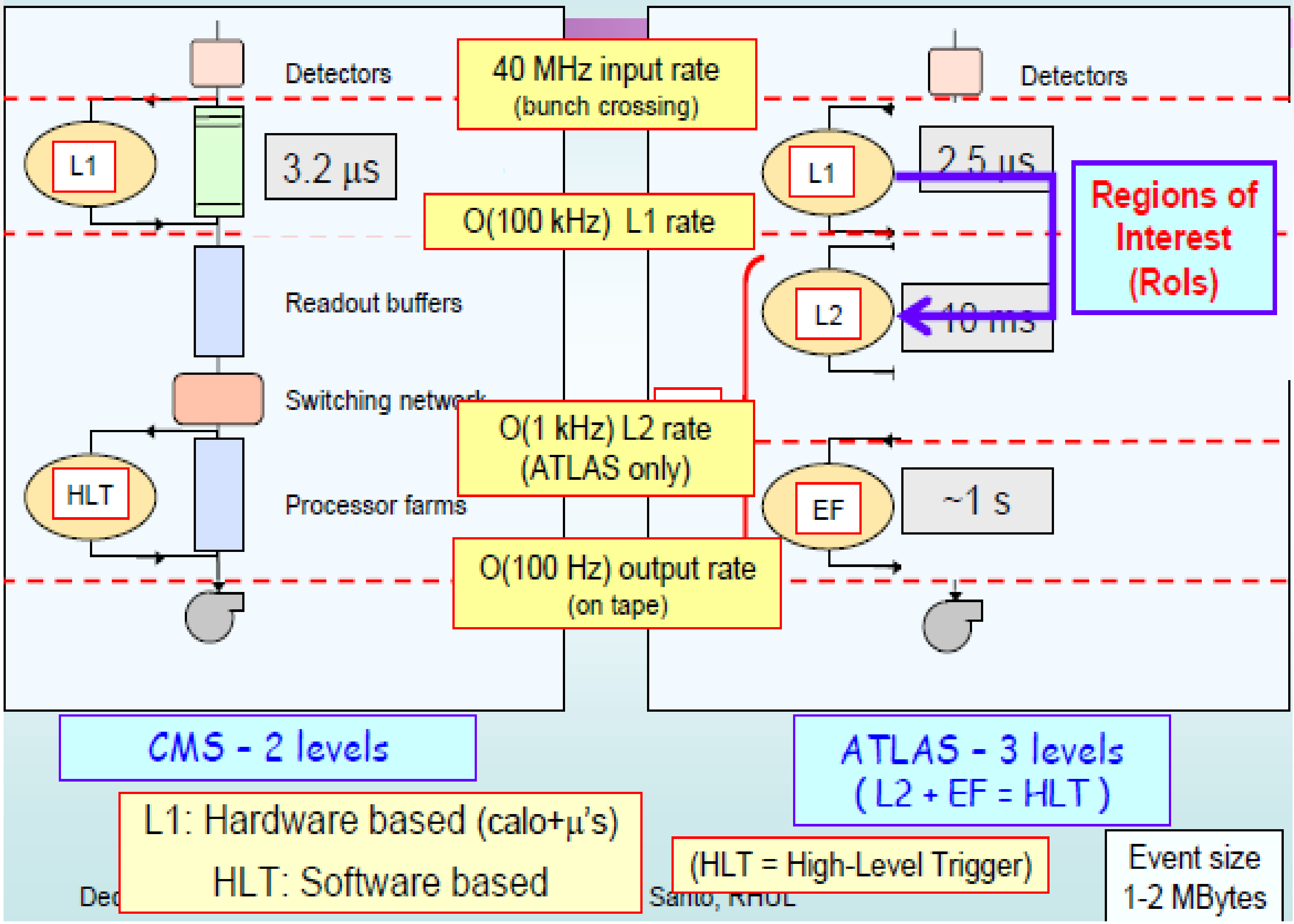
- No real thresholds
- Total cross section (including elastic) almost constant
- Some lines 'broken' going from Tevatron to LHC due to antiprotons vs protons
- Several orders of magnitude between discoveries and background



History of this first year can be summarised as: going down this plot

Triggering

- DAQ can only take O(100 Hz), so rejection factors on BG of order 1M are needed, while keeping high efficiency on rare signal events. Different stategies:



40 MHz input rate (bunch crossing)

O(100 kHz) L1 rate

O(1 kHz) L2 rate (ATLAS only)

O(100 Hz) output rate (on tape)

Regions of Interest (RoIs)

CMS - 2 levels

ATLAS - 3 levels (L2 + EF = HLT)

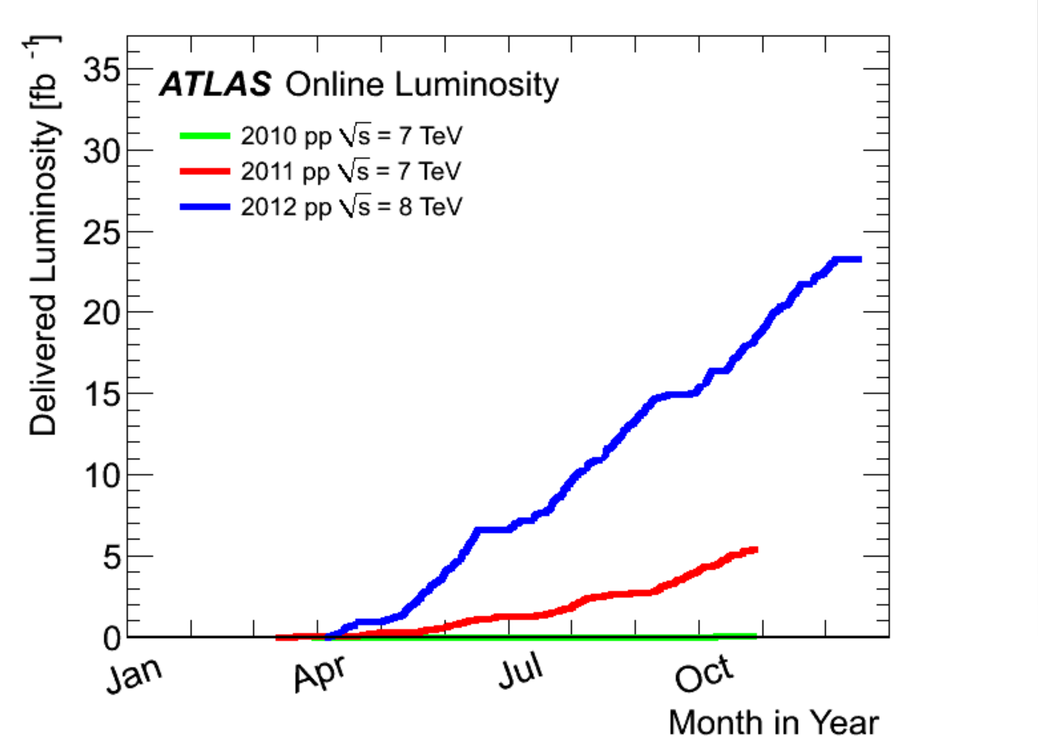
L1: Hardware based (calo+μ's)

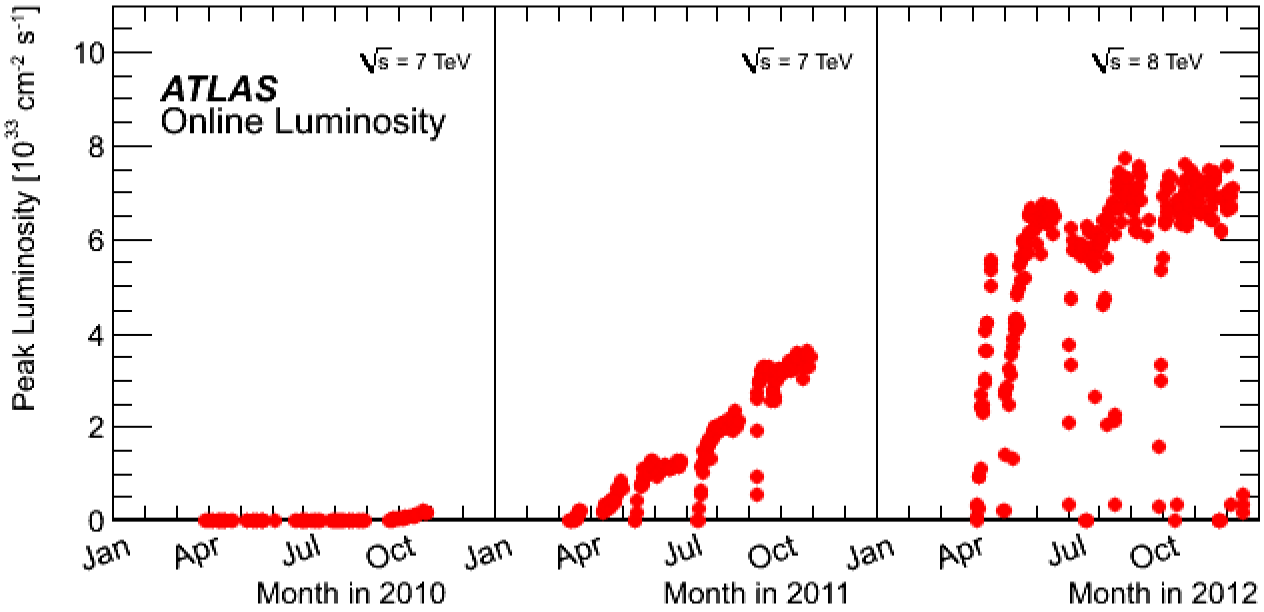
HLT: Software based

(HLT = High-Level Trigger)

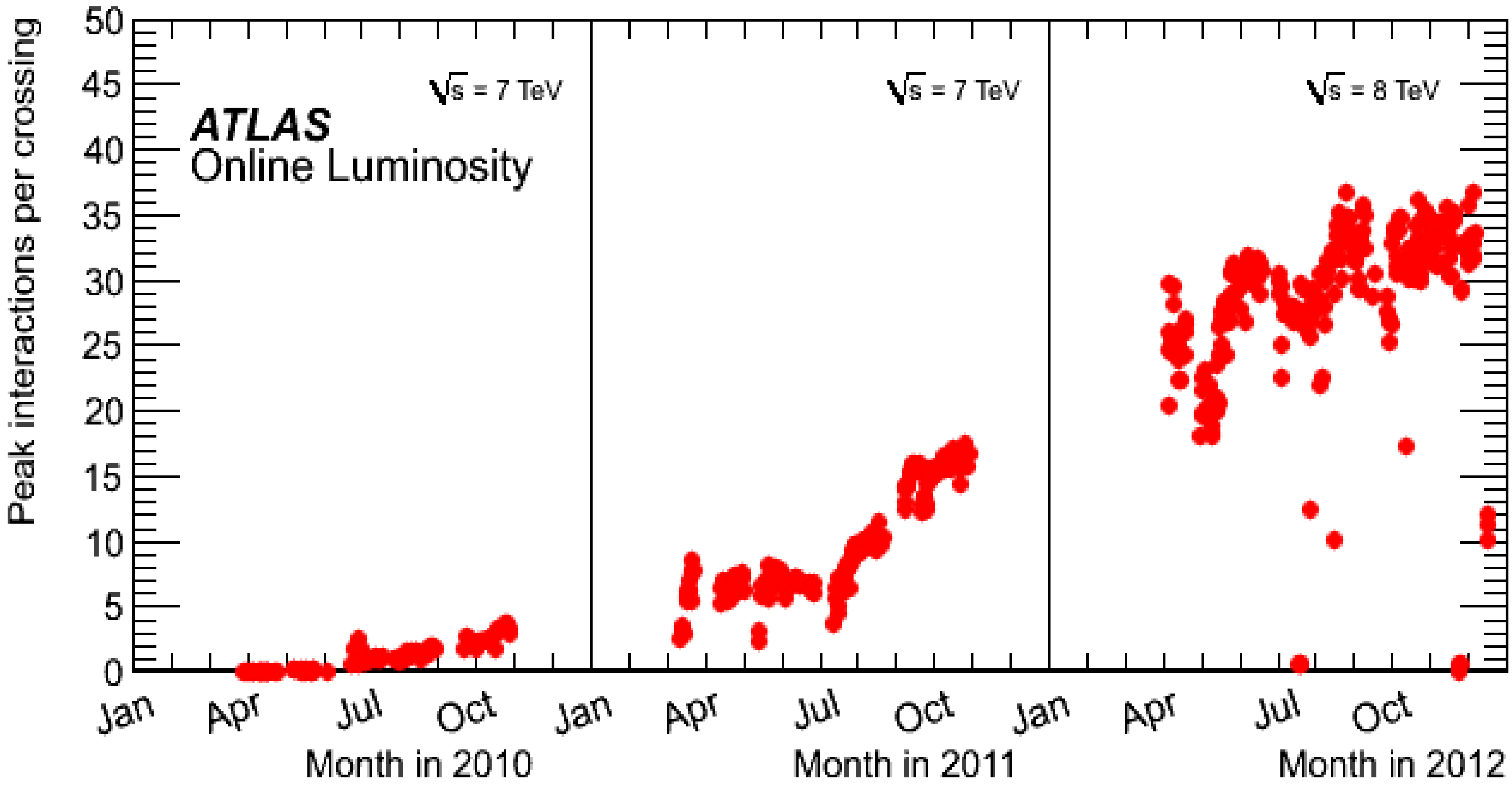
Event size 1-2 MBytes

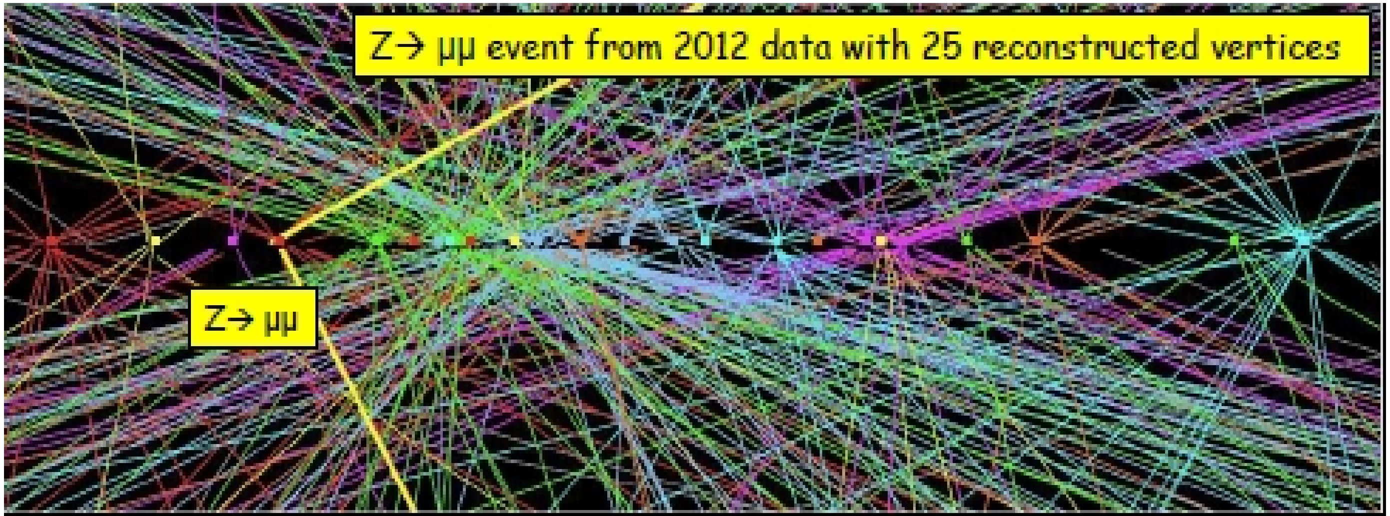
Luminosity evolution



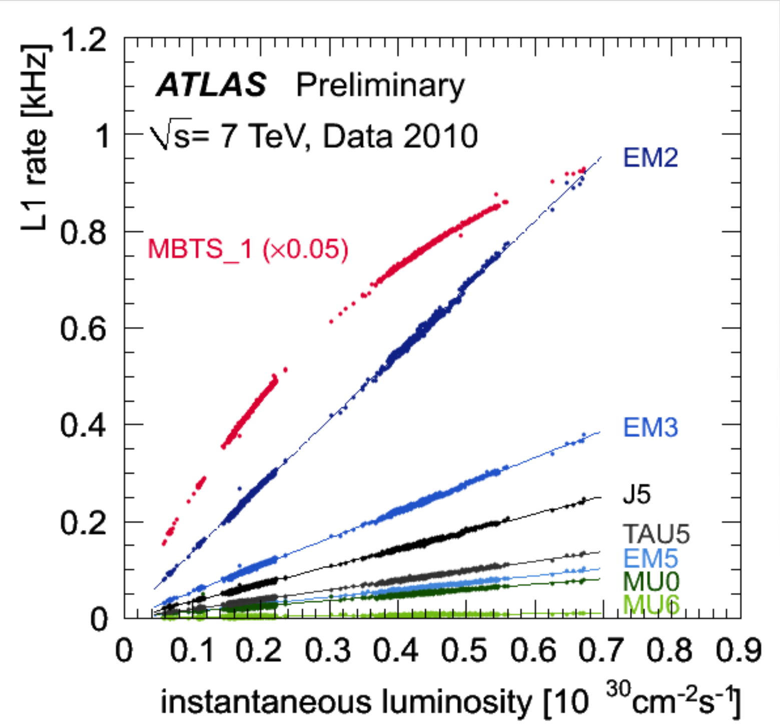


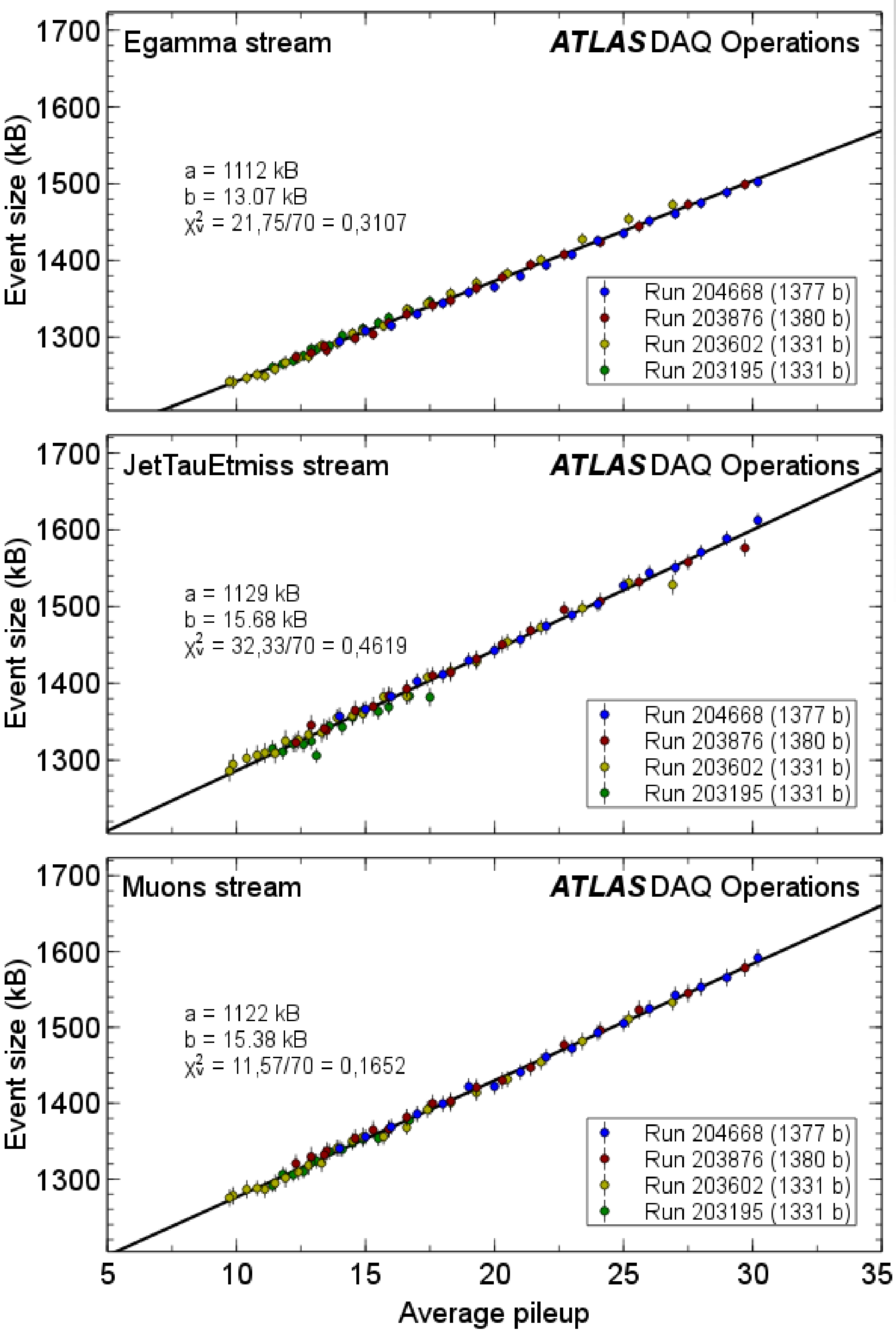
What that means for pileup





L1 Trigger rates vs luminosity

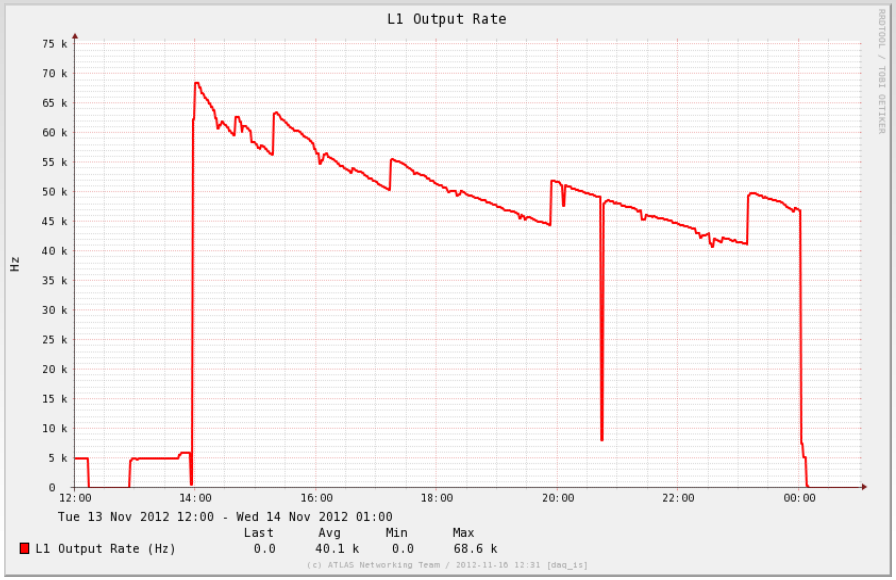


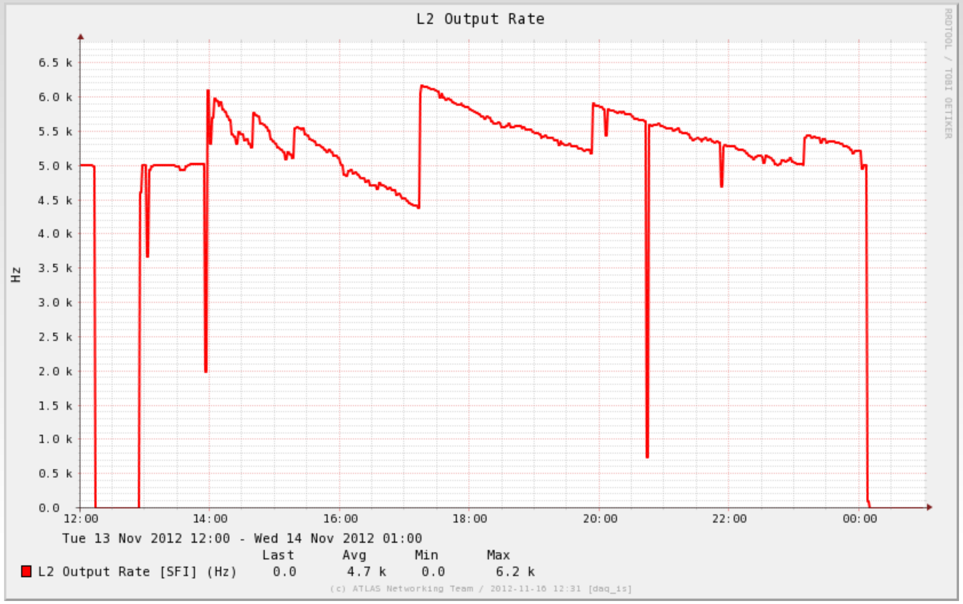


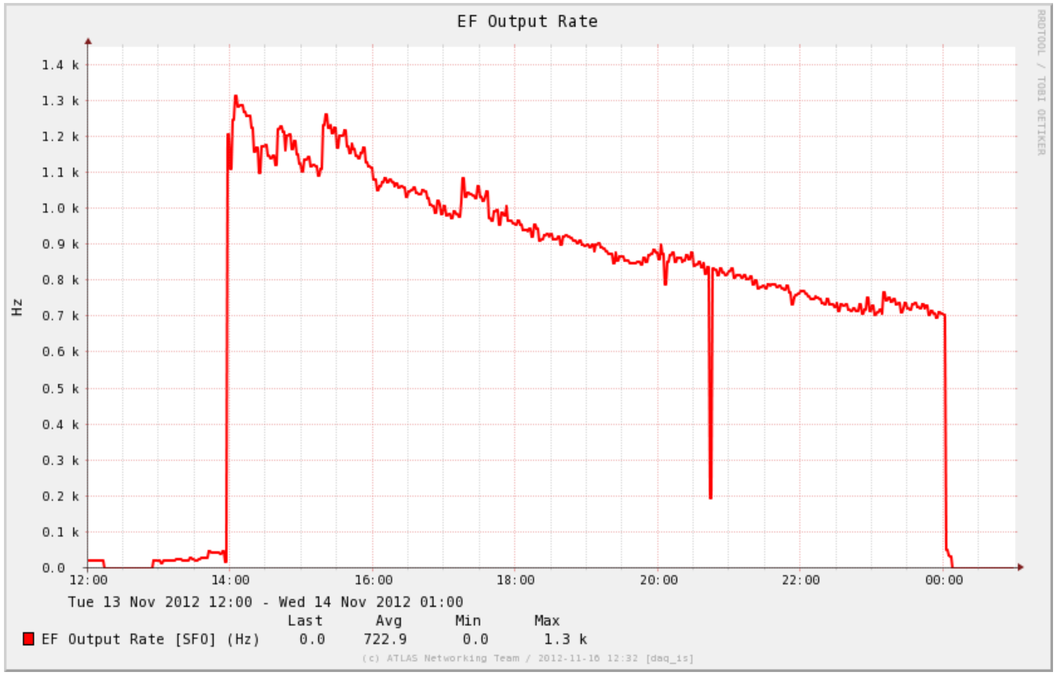
Rates still linear since in no-pileup region.

Non-linearities observed for MinBias triggers

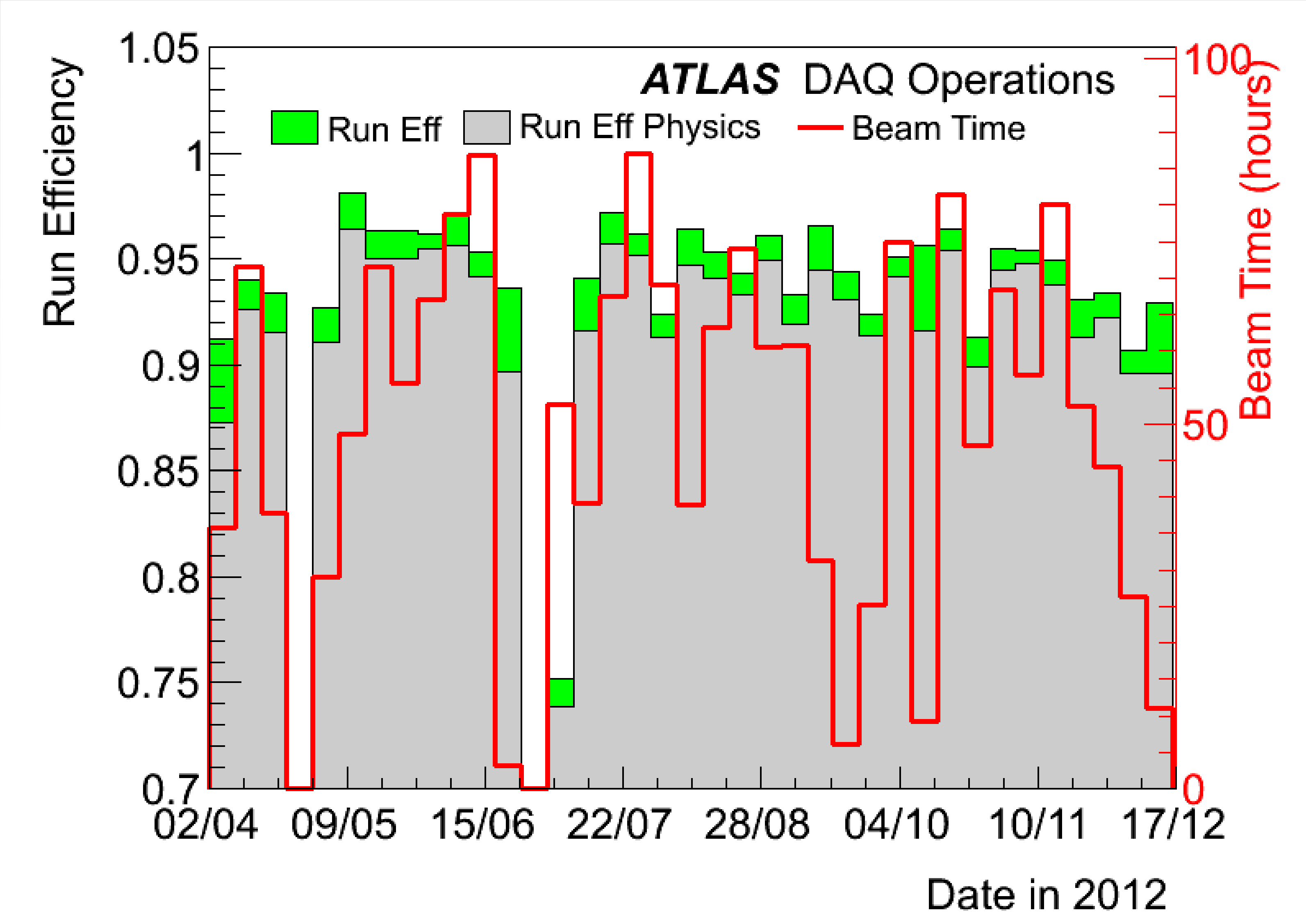
ATLAS trigger rate evolution in a typical run



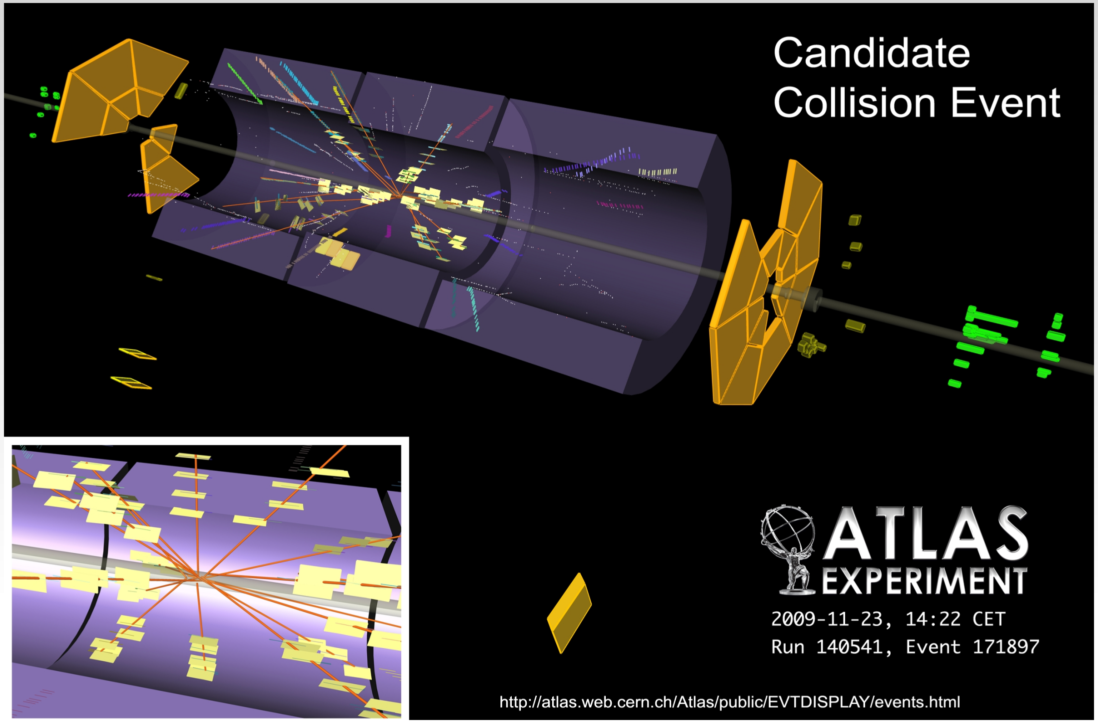




ATLAS data taking efficiency



First events in Atlas/CMS

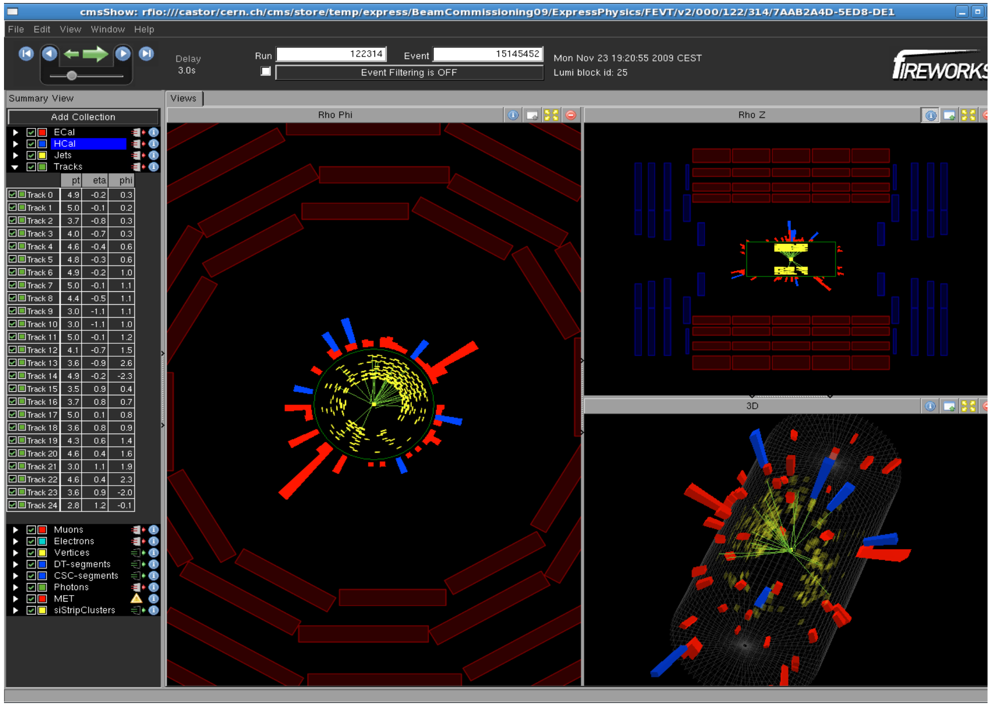


Candidate Collision Event

2009-11-23, 14:22 CET
Run 140541, Event 171897

http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

Soft collisions with just few tracks but important for alignment and trigger studies



cmsShow: rfio:///castor/cern.ch/cms/store/temp/express/BeamCommissioning09/ExpressPhysics/FEVT/v2/000/122/314/7AAB2A4D-5ED8-DE1

Delay 3.0s

Run 122314

Event 15145452

Event Filtering is OFF

Mon Nov 23 19:20:55 2009 CEST

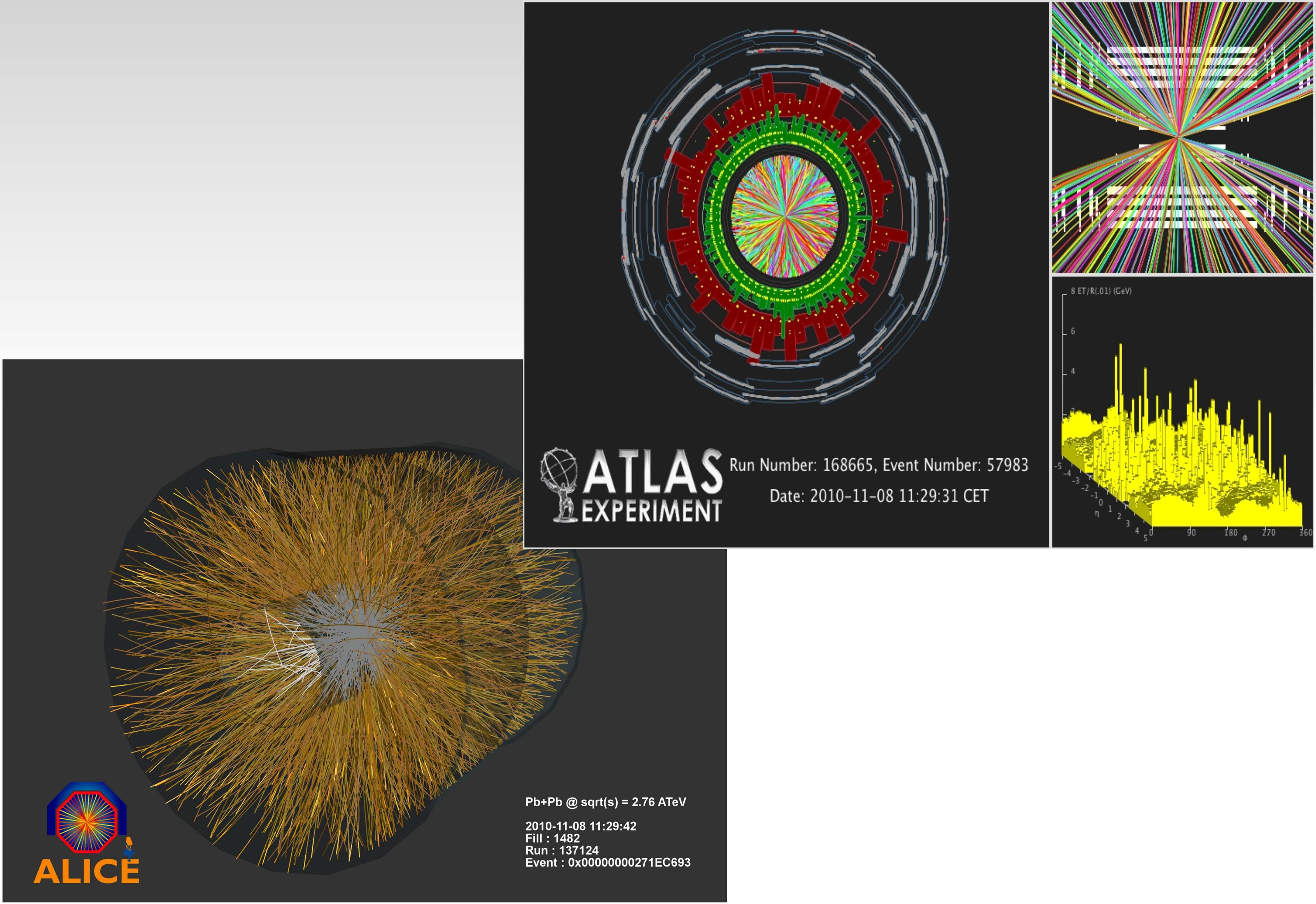
Lumi block id: 25

- ☑ ECal
- ☑ HCal
- ☑ Jets
- ☑ Tracks

	pt	eta	phi
☑ Track 0	4.9	-0.2	0.3
☑ Track 1	5.0	-0.1	0.2
☑ Track 2	3.7	-0.8	0.3
☑ Track 3	4.0	-0.7	0.3
☑ Track 4	4.6	-0.4	0.6
☑ Track 5	4.8	-0.3	0.6
☑ Track 6	4.9	-0.2	1.0
☑ Track 7	5.0	-0.1	1.1
☑ Track 8	4.4	-0.5	1.1
☑ Track 9	3.0	-1.1	1.1
☑ Track 10	3.0	-1.1	1.0
☑ Track 11	5.0	-0.1	1.2
☑ Track 12	4.1	-0.7	1.5
☑ Track 13	3.6	-0.9	2.6
☑ Track 14	4.9	-0.2	-2.3
☑ Track 15	3.5	0.9	0.4
☑ Track 16	3.7	0.8	0.7
☑ Track 17	5.0	0.1	0.8
☑ Track 18	3.6	0.8	0.9
☑ Track 19	4.3	0.6	1.4
☑ Track 20	4.6	0.4	1.6
☑ Track 21	3.0	1.1	1.9
☑ Track 22	4.6	0.4	2.3
☑ Track 23	3.6	0.9	-2.0
☑ Track 24	2.8	1.2	-0.1

- ☑ Muons
- ☑ Electrons
- ☑ Vertices
- ☑ DT-segments
- ☑ CSC-segments
- ☑ Photons
- ☑ MET
- ☑ siStripClusters

The other extreme: HI collisions



Run Number: 168665, Event Number: 57983

Date: 2010-11-08 11:29:31 CET

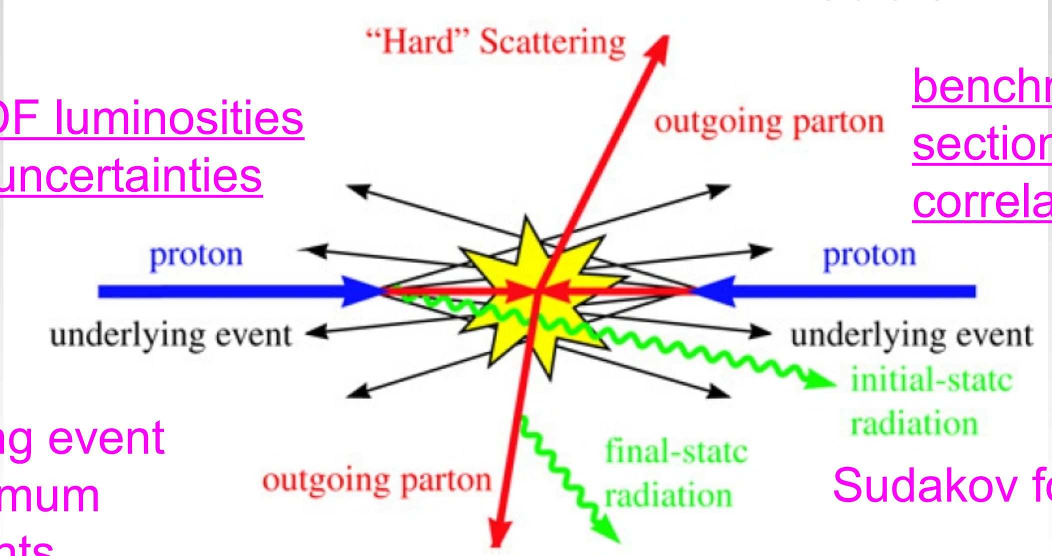
Pb+Pb @ sqrt(s) = 2.76 ATeV

2010-11-08 11:29:42
Fill : 1482
Run : 137124
Event : 0x00000000271EC693

Physics in a hadron collider

LO, NLO and NNLO calculations

K-factors



PDF's, PDF luminosities and PDF uncertainties

benchmark cross sections and pdf correlations

underlying event and minimum bias events

Sudakov form factors

jet algorithms and jet reconstruction

$$\sigma = \sum_{i,j} \int_0^1 dx_1\, dx_2\, f_i(x_1,\mu)\, f_j(x_2,\mu)\, \hat{\sigma}_{ij}$$

Parton distribution functions

The functions f_1, f_2 (PDF's) are fractional momentum distributions (x = Pp/Pbeam) of the partons inside a proton.

Gluons and quarks other than the valence (uud) are present, with steeply falling distributions

This is why for low-mass objects a pp or p-antip collider are almost the same

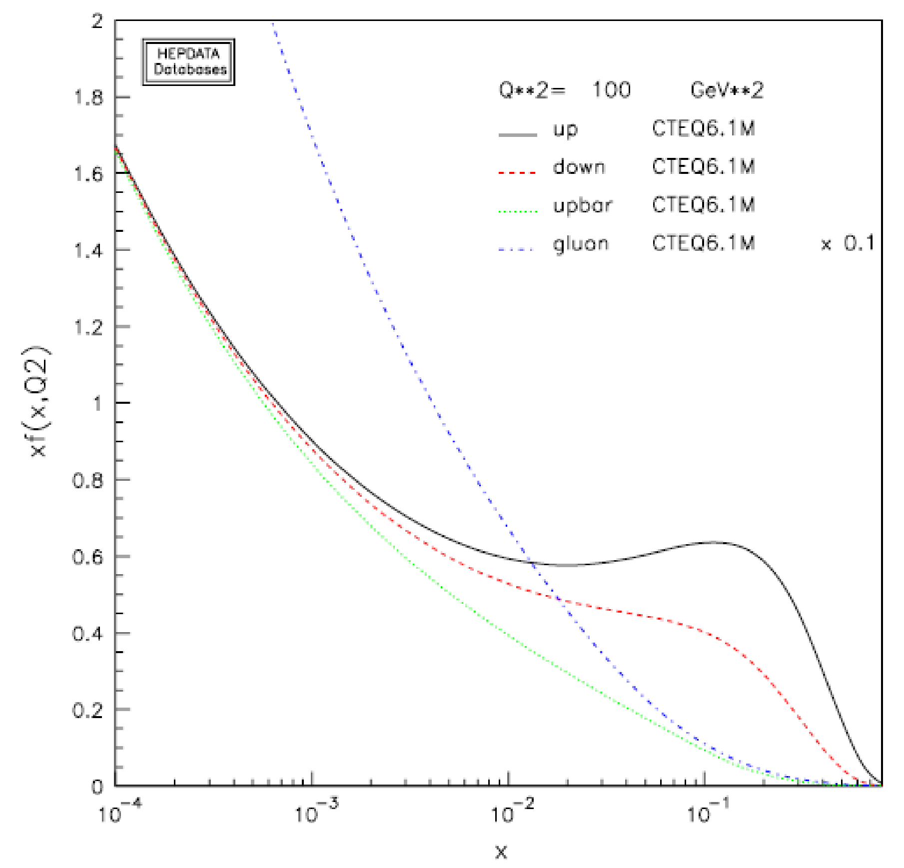


Figure 27. The CTEQ6.1 parton distribution functions evaluated at a Q of 10 GeV.

Typically the two colliding partons will have different x → event will be longitudinally unbalanced (Lorentz-boosted)

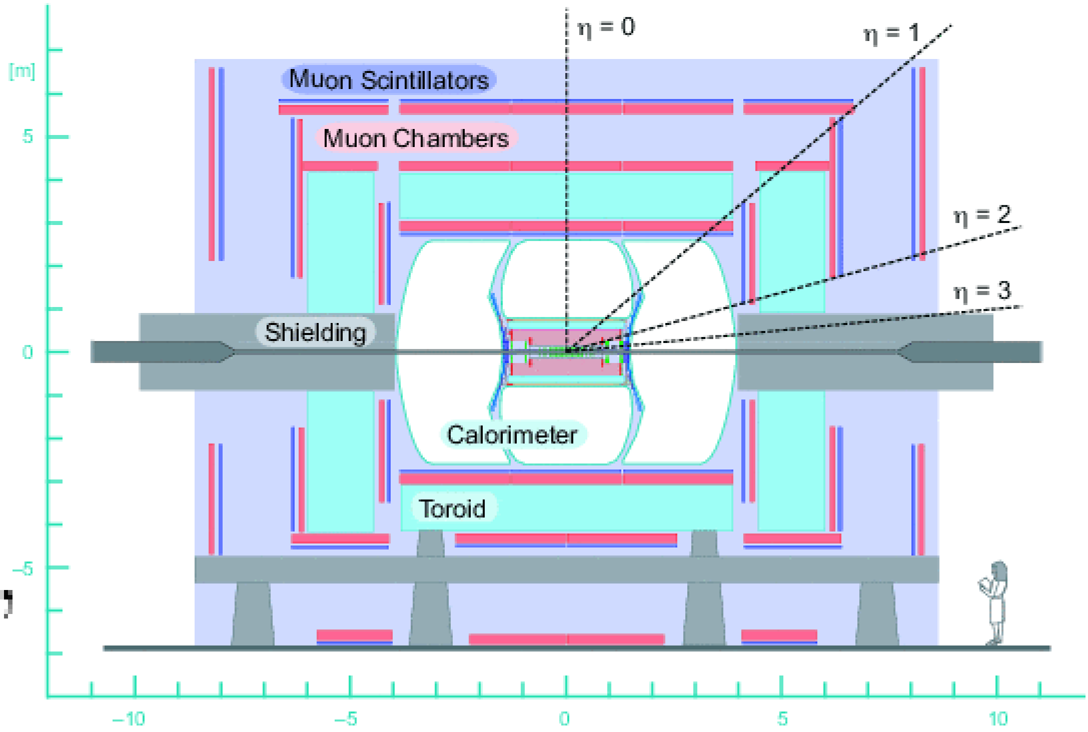
Relevant variables

- Only variables invariant under z-boost should be used.
- This is why cuts are expressed in terms of Et and not E, and instead of the angle θ we use rapidity

$$\phi_z = \frac{1}{2}\log_e \frac{E + p_z c}{E - p_z c}$$

It depends on the mass of an object, so it cannot directly reference to a detector location; for that we use pseudorapidity, equal to rapidity for massless particles:

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$



Kinematic region of the LHC

Note that the data from HERA and fixed target cover only part of kinematic range accessible at the LHC

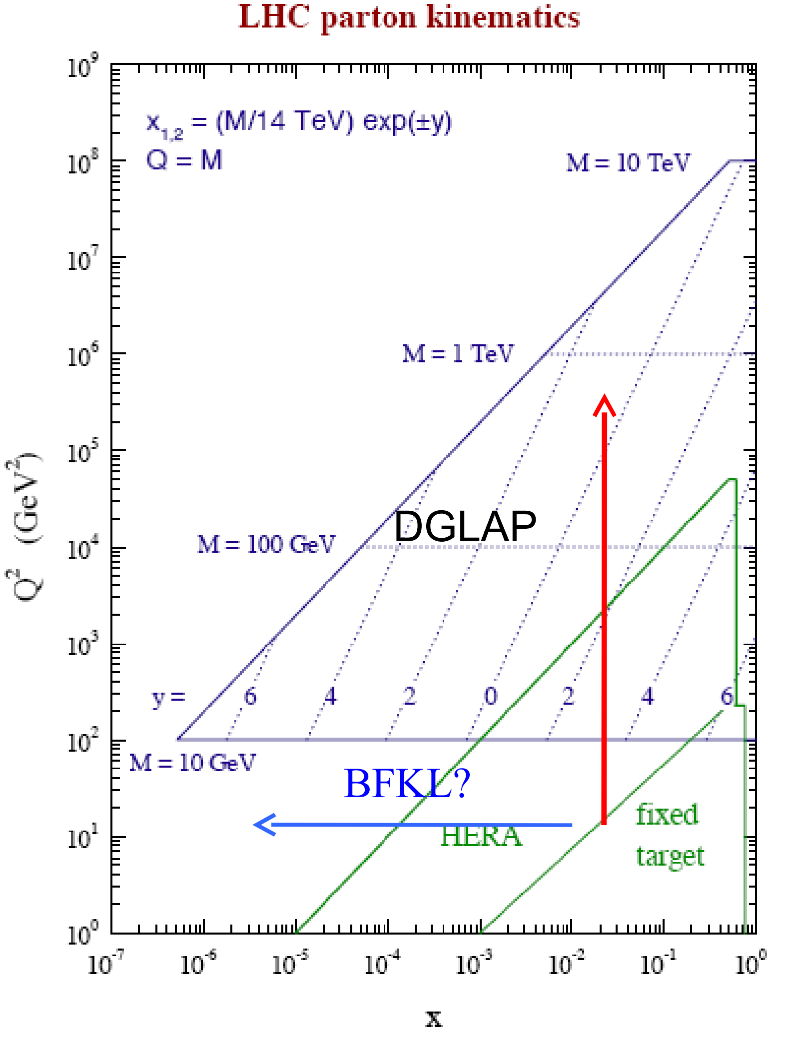
We will access pdf’s down to 1E-6 (crucial for the underlying event) and Q^2 up to 100 TeV^2

We can use the DGLAP equations to evolve to the relevant x and Q^2 range, but…

we’re somewhat blind in extrapolating to lower x values than present in the HERA data, so uncertainty may be larger than currently estimated

we’re assuming that DGLAP is all there is; at low x BFKL type of logarithms may become important

$$\frac{d\sigma}{dM^2 dy} = \frac{\hat{\sigma}_0}{Ns}\left[\sum_k Q_k^2 (q_k(x_1, M^2)\bar{q}_k(x_2, M^2) + [1 \leftrightarrow 2])\right]$$

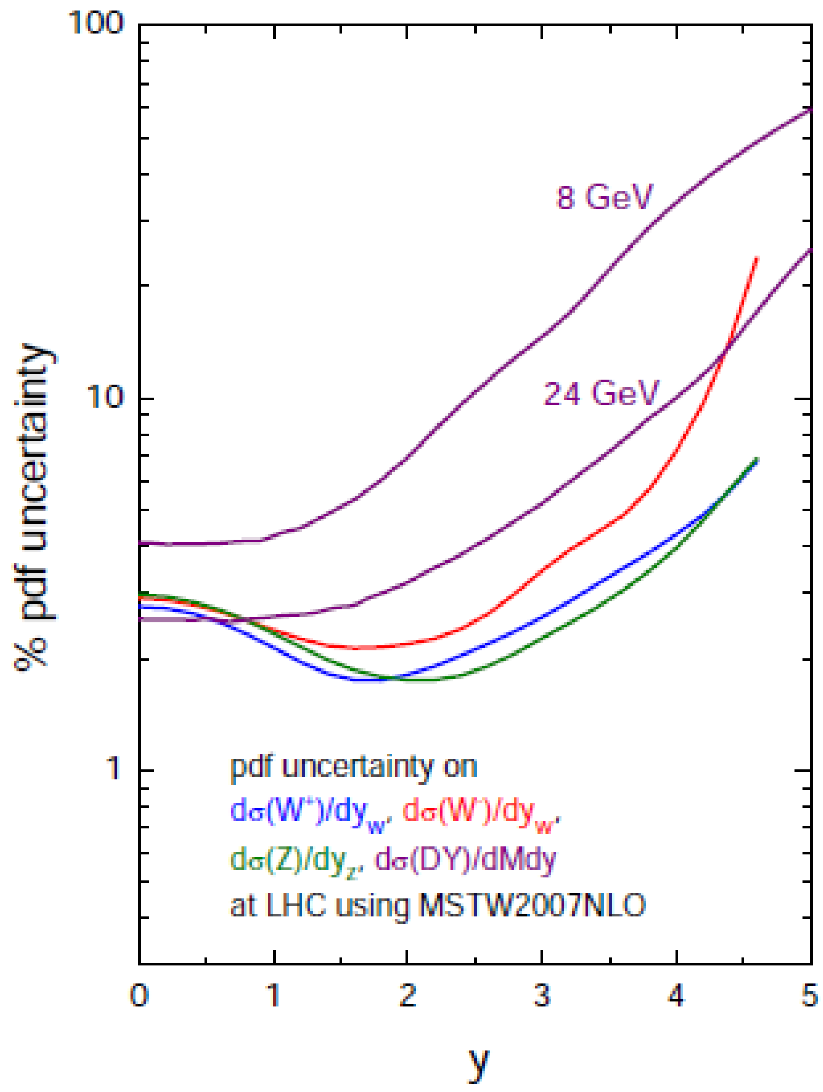


Pdf uncertainties

Uncertainty on $\sigma(Z)$ and $\sigma(W^+)$ grows at high rapidity.

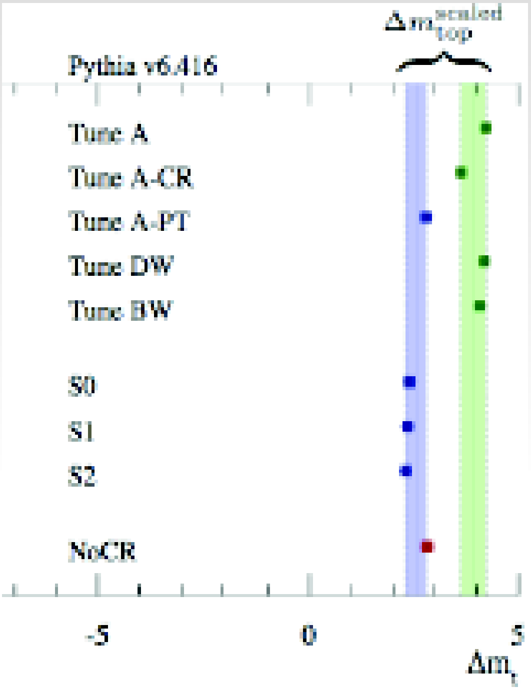
Uncertainty on $\sigma(W^-)$ grows more quickly at very high y – depends on less well-known down quark.

Uncertainty on $\sigma(\gamma^\star)$ is greatest as y increases. Depends on partons at very small x.



The underlying event and the minimum bias

- UE: everything apart from the hard scattering (beam remnant, Multiple Parton Interctions, etc.)
- Will pollute all your physics events (especially ”rapidity gaps”), and influence precision measurements
- normally softer (but with large fluctuations)

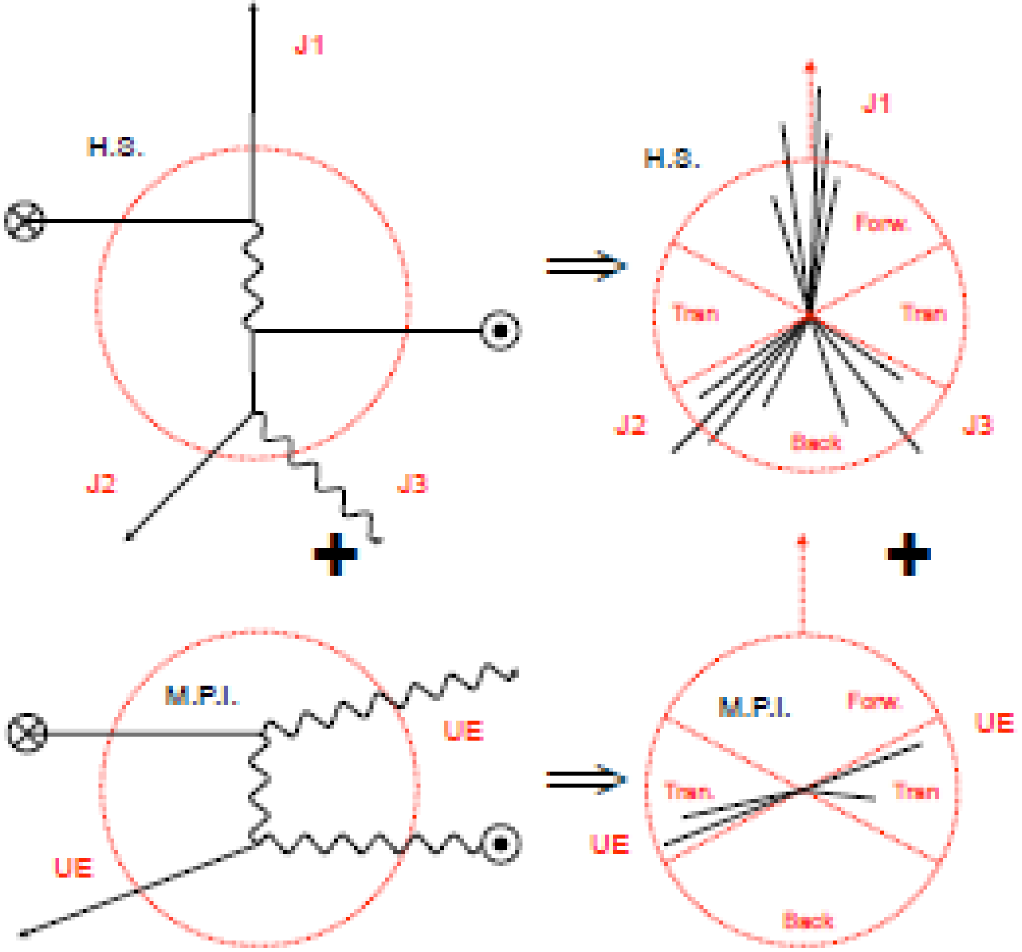


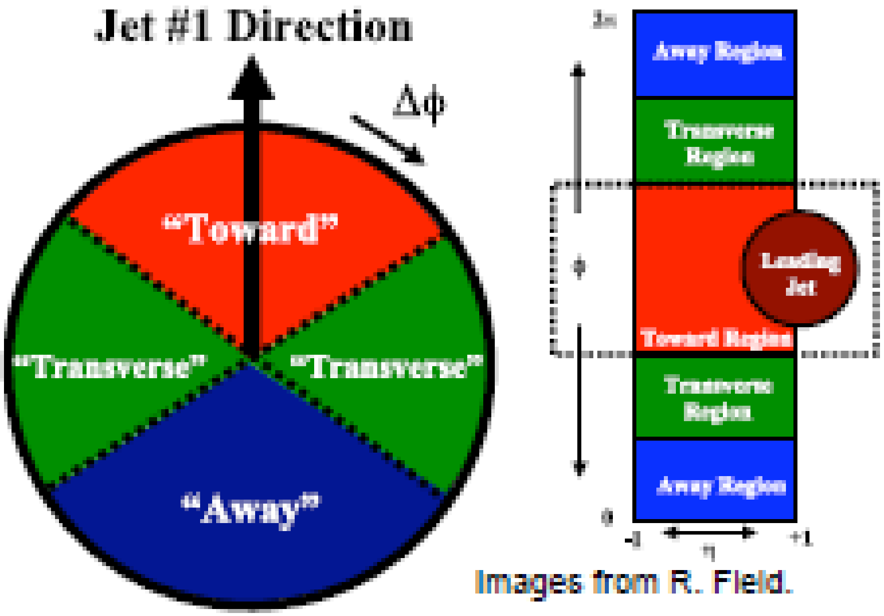
•We are in the realm of non-perturbative QCD, so only possible to do empiric models to be tuned on data
•These models are similar to those use to model soft scattering events (the Minimum Bias), which are the events we are taking right now
•Various models implemented in generators: Pythia, Herwig, Phojet

UE Characterization

- Hard Scatter yields* 2 or 3 hard jets.

  *Given sufficient qualifying statements…
- Two equally hard jets will be roughly back-to-back.
- Additional interactions yield softer particles whose directions are not correlated to the hard scatter axis.
- Fragmentation, especially due to connections to remnants, can yield additional particles.
- Three equally hard jets are roughly at $2\pi/3$ intervals.
- $\pi/3 < |\Delta\varphi| < 2\pi/3$ and $|\eta| < 1$ defines the transverse region.
- For the third hardest jet to be in the transverse region it must be softened.





Images from R. Field.

What is soft-QCD?

QCD = Quantum ChromoDynamics (i.e. the strong force)

soft = low momentum transfer

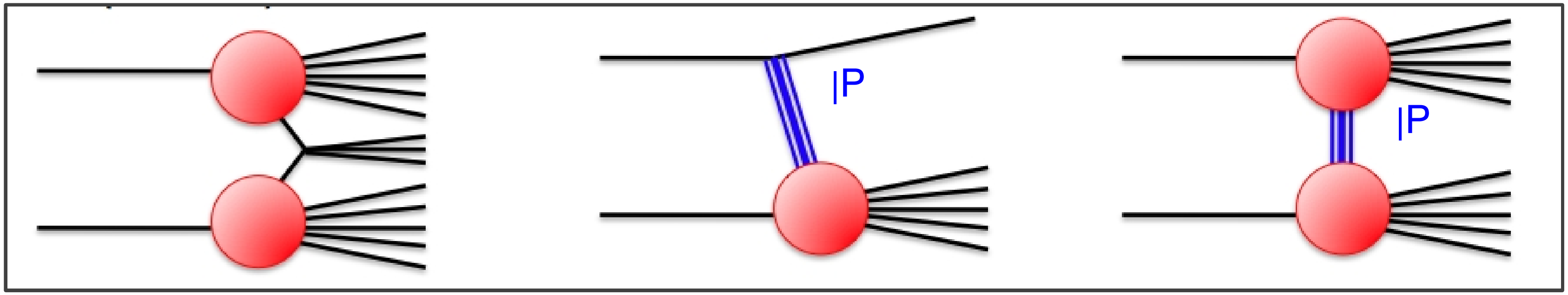
These are the dominant types of interaction at hadron colliders

What is soft-QCD?

Elastic interaction: A(pA) + B(pB) ➘ A(pA‘) + B(pB‘)

Inelastic interaction: A + B ➘ Σxi (≠ A + B)

Dominant processes in inelastic hadron-hadron interactions :



Non-Diffractive
(ND) σ~49 mb

Single-Diffractive-Dissociation
(SD) σ~14 mb

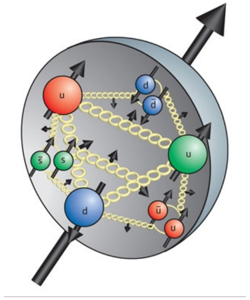
Double-Diffractive-Dissociation
(DD) σ~9 mb

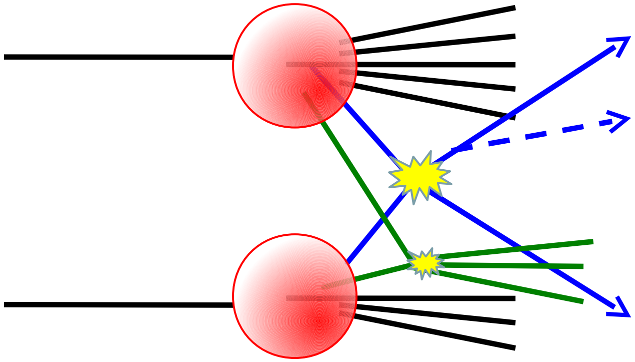
@ 7 TeV

|P = Pomeron (quantum numbers of the vacuum)

What is soft-QCD?

Soft-QCD processes also occur in the same proton-proton interaction as a (more interesting) hard interaction:





Multiple Parton Interactions (MPI)

The Underlying Event (UE) is everything not associated with the hard parton-parton interaction

Why do we care ?

These processes cannot be calculated from first principles (the strong coupling blows up at low scales and perturbative calculations are not possible). What is going on at these scales?

soft-QCD affecting the high pT physics program at hadron colliders:

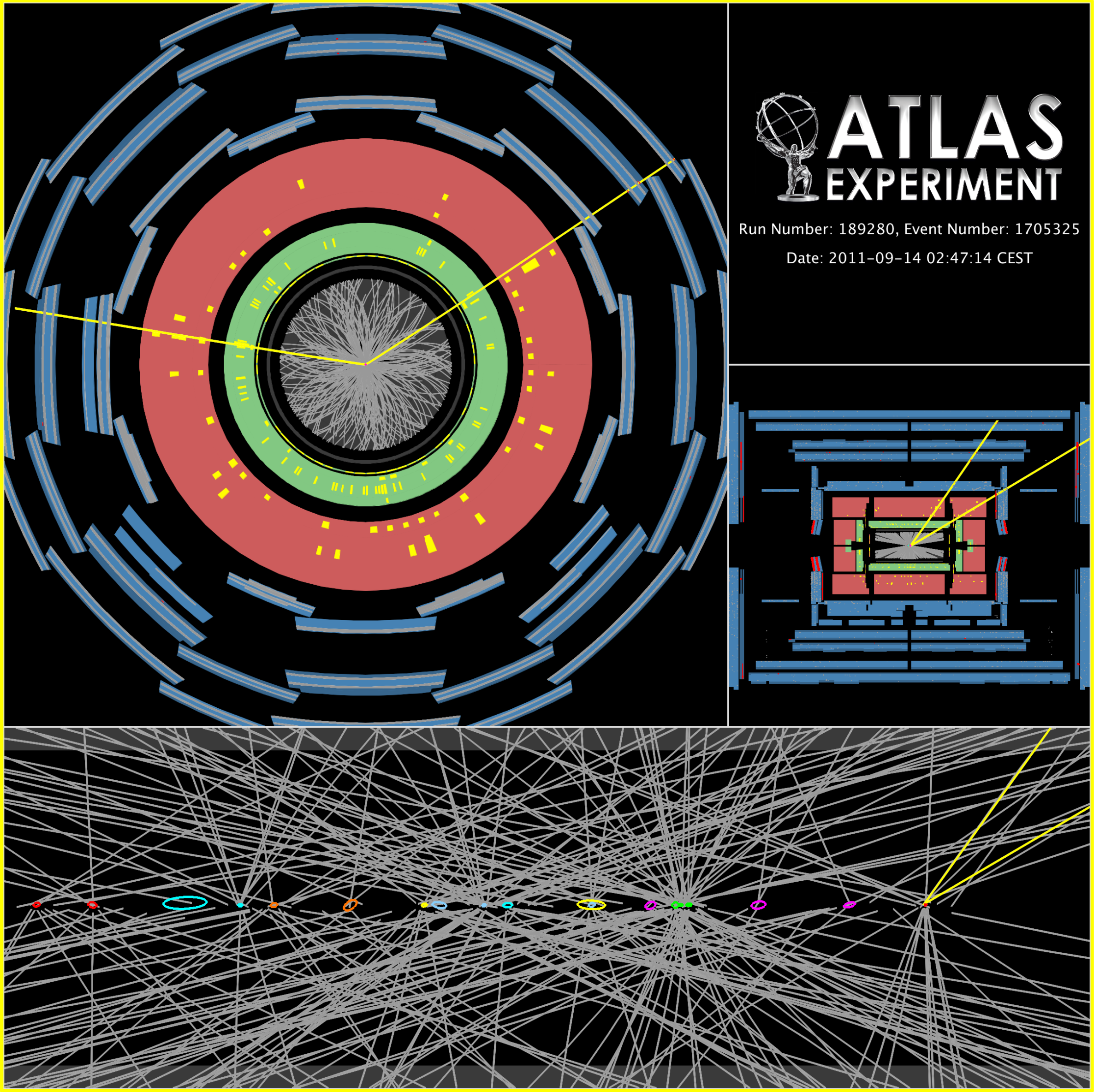
Pileup: LHC ~20 proton-proton interactions at the same time, they will almost always be soft-QCD processes

Multi Parton Interactions: An interesting parton-parton interaction will have many additional parton-parton interactions occurring in the same proton-proton interaction, they will almost always be soft-QCD processes

Therefore we had better have a good model of these processes! Can affect simulations of lepton ID, ETmiss resolution, jets, jet vetos,…

Pileup

Important for understanding 20 pp interactions on top of your Higgs!!



Monte Carlo Event Generators

See Glen Cowan’s course next week for all the details

In brief:

Theoretical tools that simulate events at colliders

Extensively used to simulate signal and background processes, to help us understand our data and enable us to make measurements

High pT interactions are calculated using perturbation theory

Soft-QCD processes use phenomenological models with theoretical motivation that must be validated against data

These models contain parameters that must be tuned to the data

It is therefore necessary to make measurements of soft-QCD processes

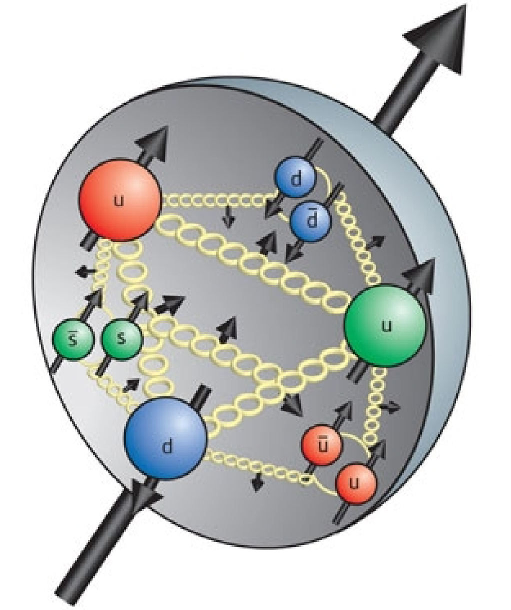
Soft-QCD models

e.g. Pythia

QCD 2→ 2 scattering		~ αS2(pT2)/pT4
Dampen divergence at low pT	↘	~ αS2(pT2 + pT02)/(pT2 + pT02)2

smaller pT0 ↘ more low pT activity

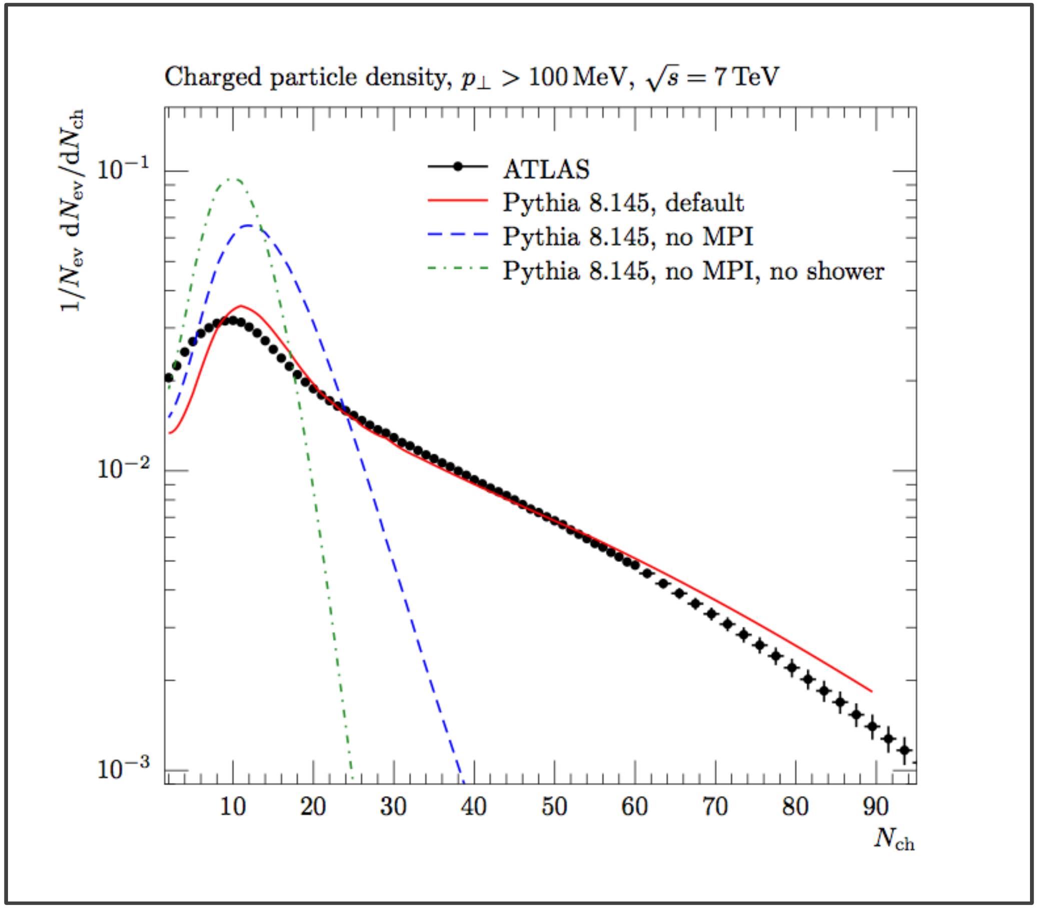
Screening : At low pT wavelength of exchanged particle becomes too large to resolve colour charges



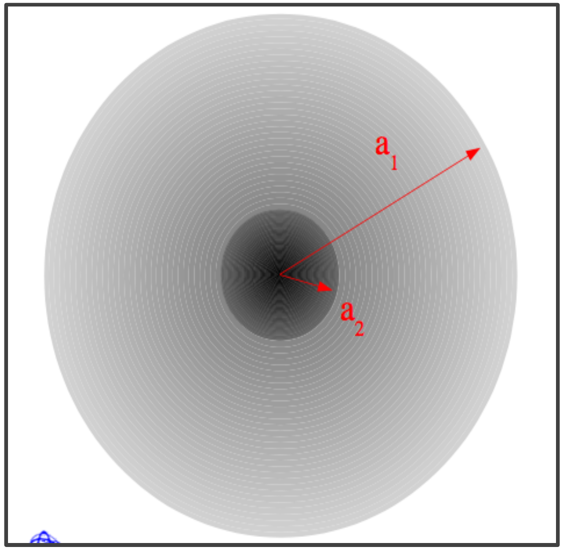
pT0 = P1 (ECOM / 1.8 TeV) P2

Multiple Parton Interactions

The soft-QCD models need to include MPI



Soft-QCD models



Matter distribution in proton described by double Gaussian

P3 = fraction in core Gaussian
P4 = a2 / a1

(denser matter distribution ↘ more multiple interactions ↘ more activity)

Experimental Measurements

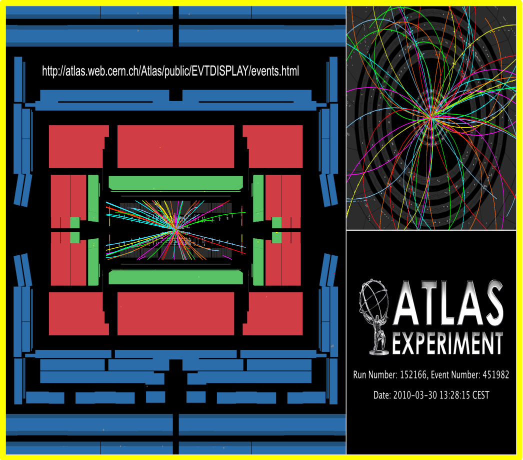
1. Minimum Bias
2. Underlying Event
3. Total cross-section
4. Diffractive cross-sections
5. Particle Correlations

1. Minimum Bias
2. Underlying Event
3. Total cross-section
4. Diffractive cross-sections
5. Particle Correlations

Minimum bias measurements

Minimum bias adj. experimental term, to select events with the minimum possible requirements that ensure an inelastic collision occurred.

- Exact definition depends on detector (and analysis)
- Typically measure kinematics (multiplicity, pT and η spectra, etc) of charged particles in “minimum bias” events using central tracking detectors
- Monte Carlo parameters will be tuned to these distributions



Charged particles moving through a magnetic field will bend by an amount inversely proportional to pT

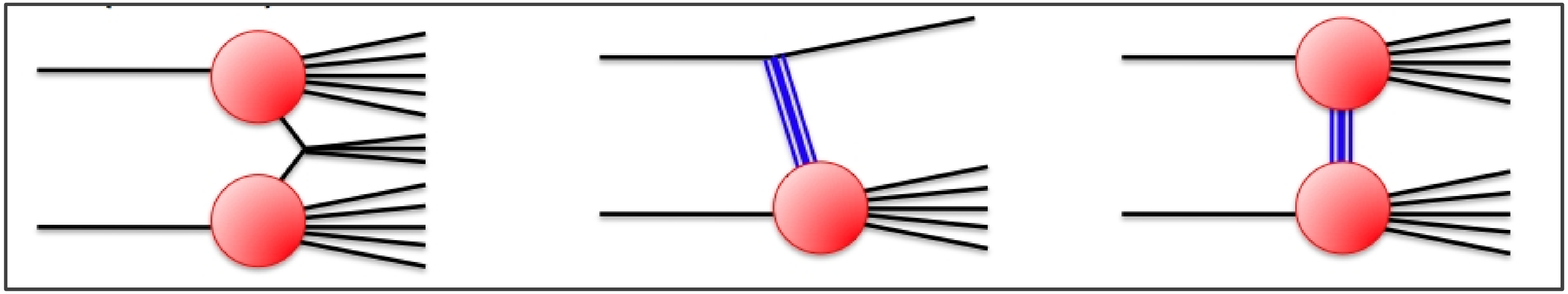
e.g. ATLAS: (a) At least two charged particles with pT > 100 MeV, $|\eta| < 2.5$ (most inclusive)
(b) At least six charged particles with pT > 500 MeV, $|\eta| < 2.5$ (suppresses diffraction)

definition of minimum bias in each analysis

Measurement philosophy

How should you do a measurement that is optimally useful for theory validation and MC tuning?

- Correct measurements for detector inefficiencies and resolutions (e.g. measure pT spectrum of charged particles, not of ATLAS tracks)
- No extrapolations into regions not “seen” by ATLAS (such as very low pT or far-forward particles)
  - We measure what we see, not what the MC tells us we should have seen!
- No corrections for diffractive events (rather make reproducible cuts that suppress diffraction) ~~Non-Single-Diffractive~~
  - On an event-by-event basis we do not know what process occurred



Triggering the events

Measurement performed with early data

Few interactions per crossing (mean ~ 0.007)

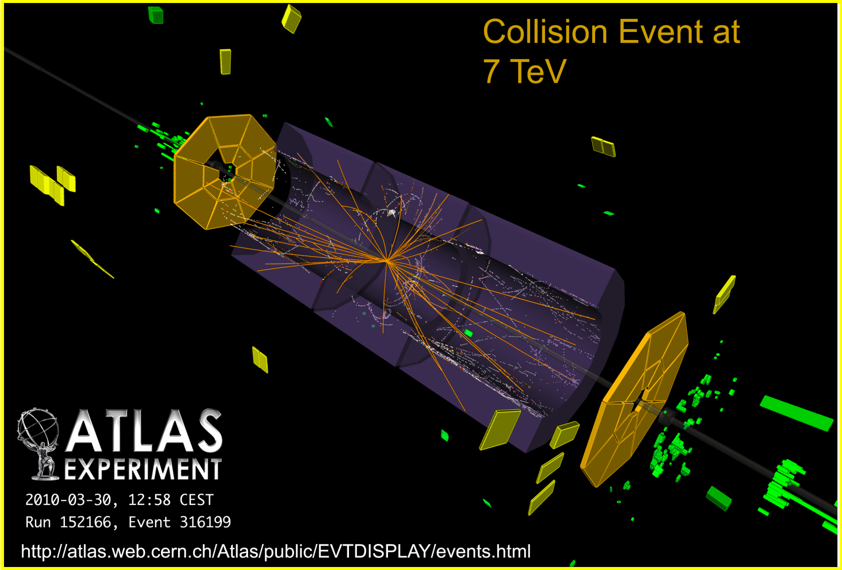
~ No additional interactions

But … 99.3% of beam crossings have no interaction!

Need to “trigger” on inelastic interactions

Use Minimum Bias Trigger Scintillators (very inclusive)

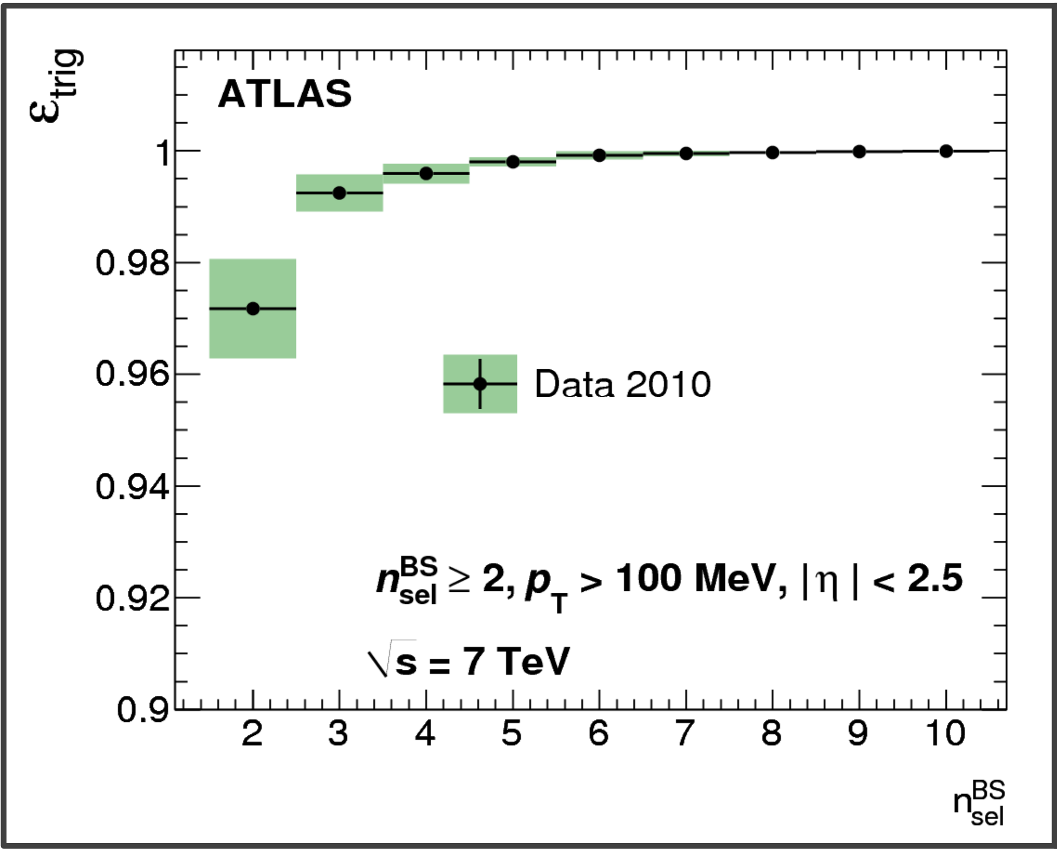
Minimum Bias Trigger Scintillator disks trigger on any charged particle with $2.09 < |\eta| < 3.84$

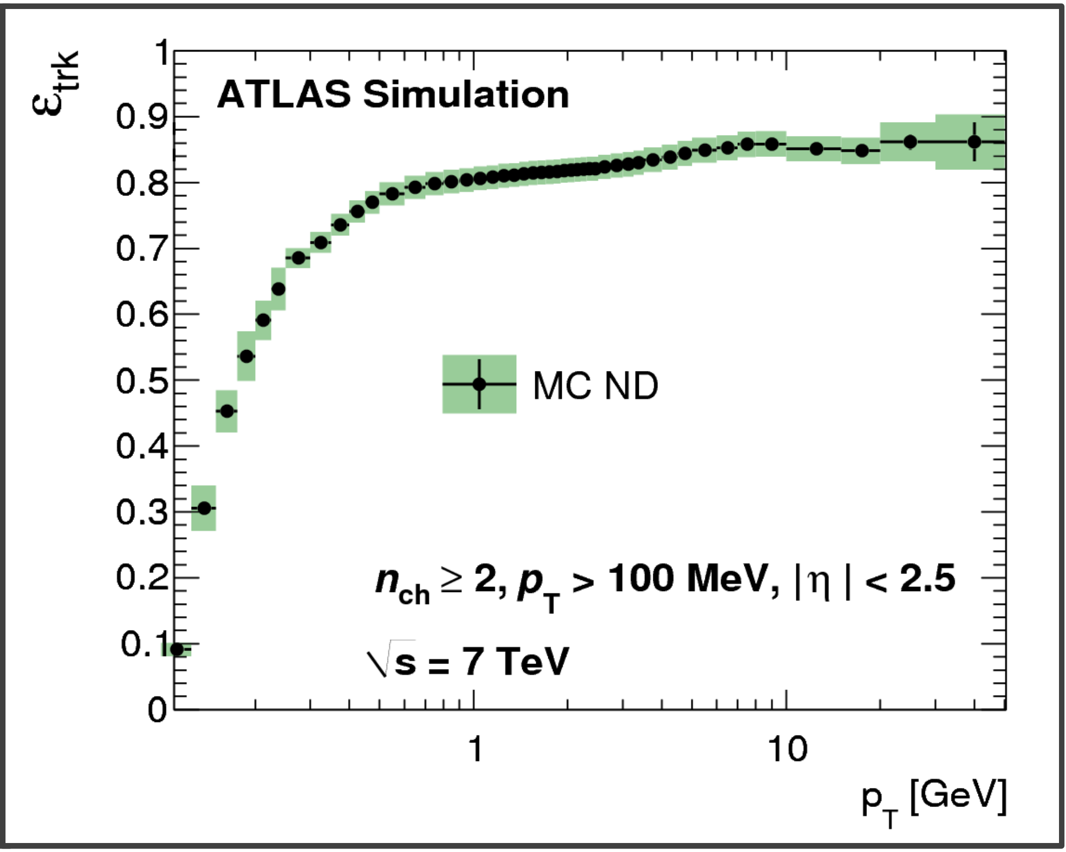


Correcting the data

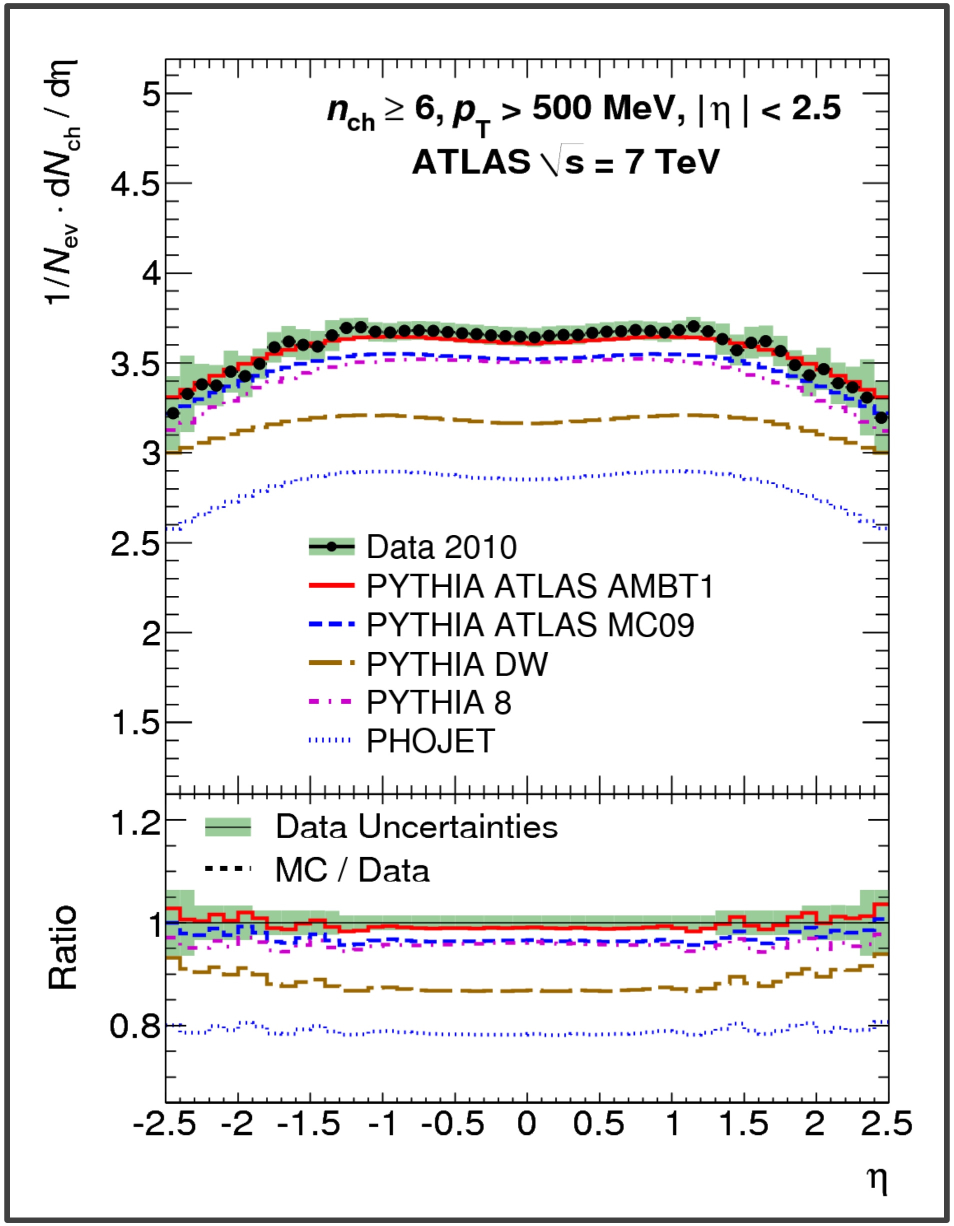
Trigger efficiency from data (small “control” sample recorded with different trigger)

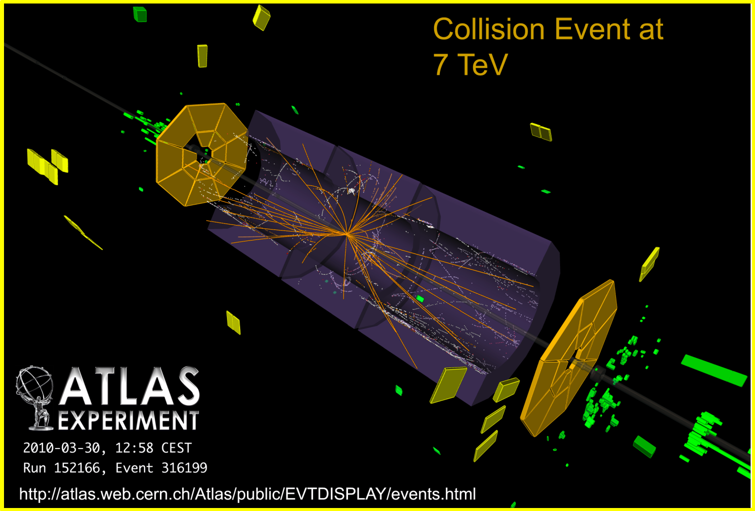
Tracking efficiency from Monte Carlo with GEANT detector simulation (systematic uncertainties determined from checks with data)





η spectra

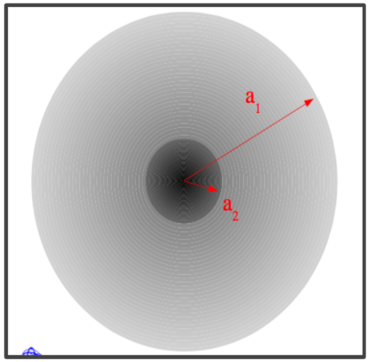




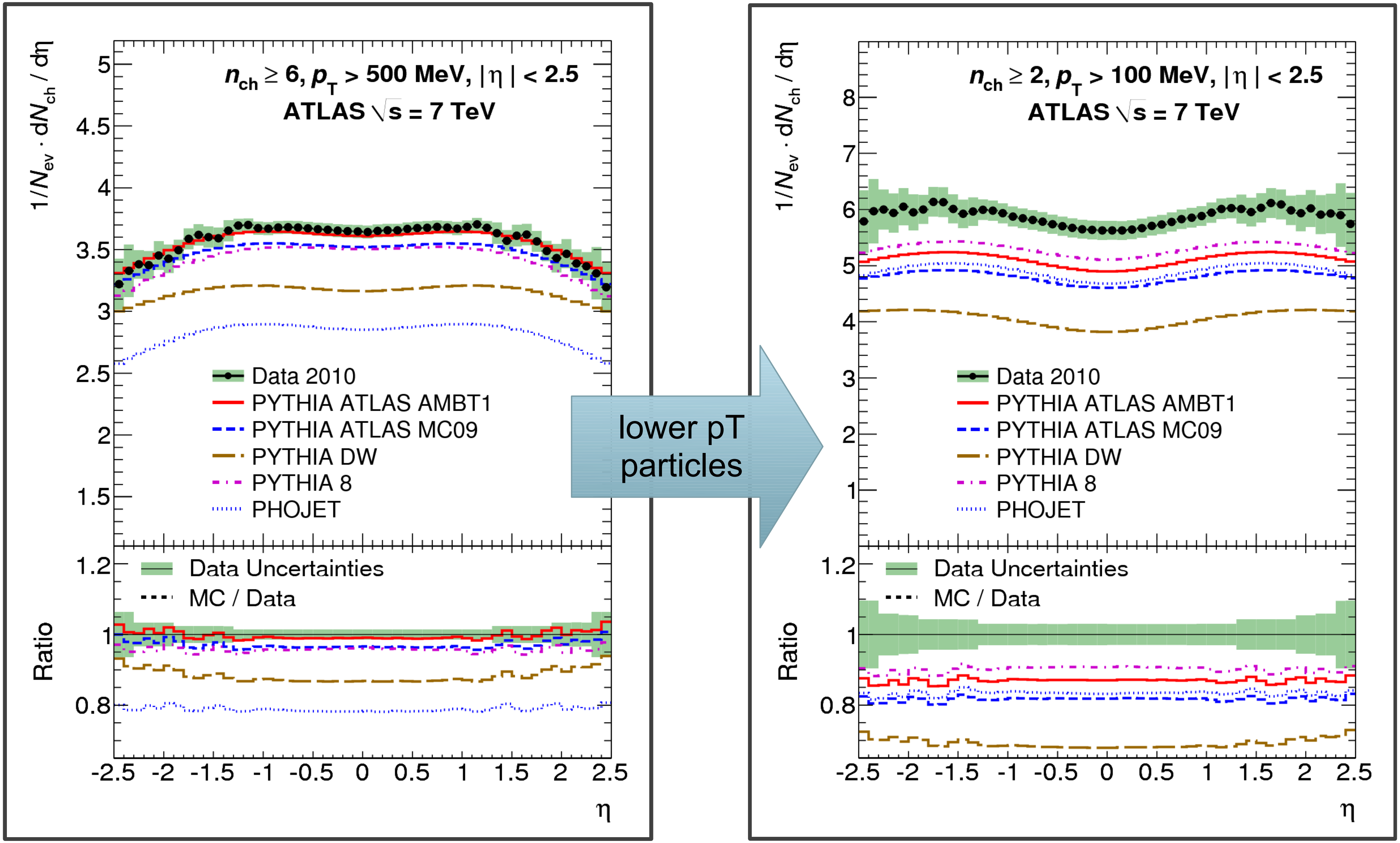
dNch/dη : Number of charged particles per unit η

All but Pythia AMBT1 are tuned to Tevatron data

Slight increase in activity in AMBT1 (achieved by a denser proton)

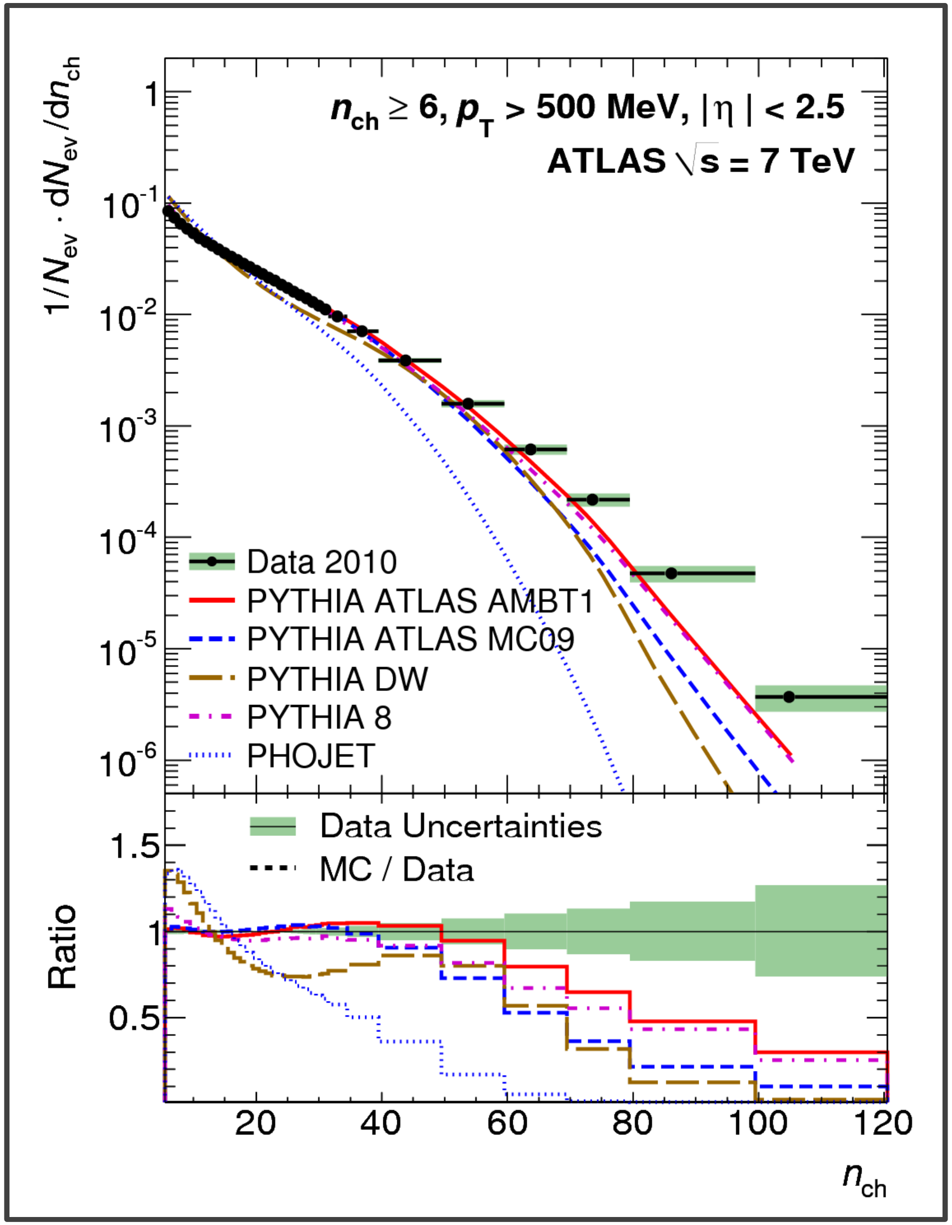


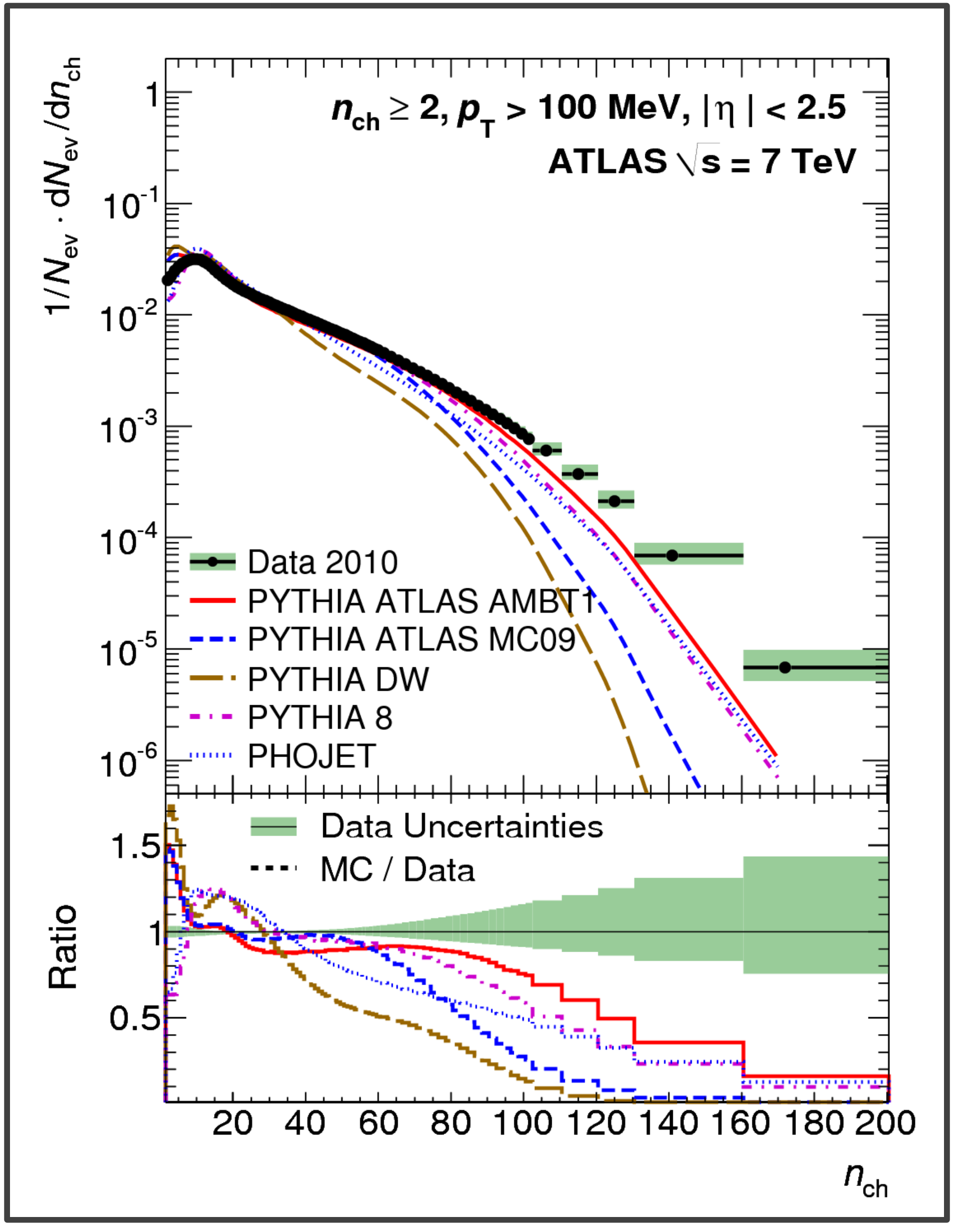
η spectra



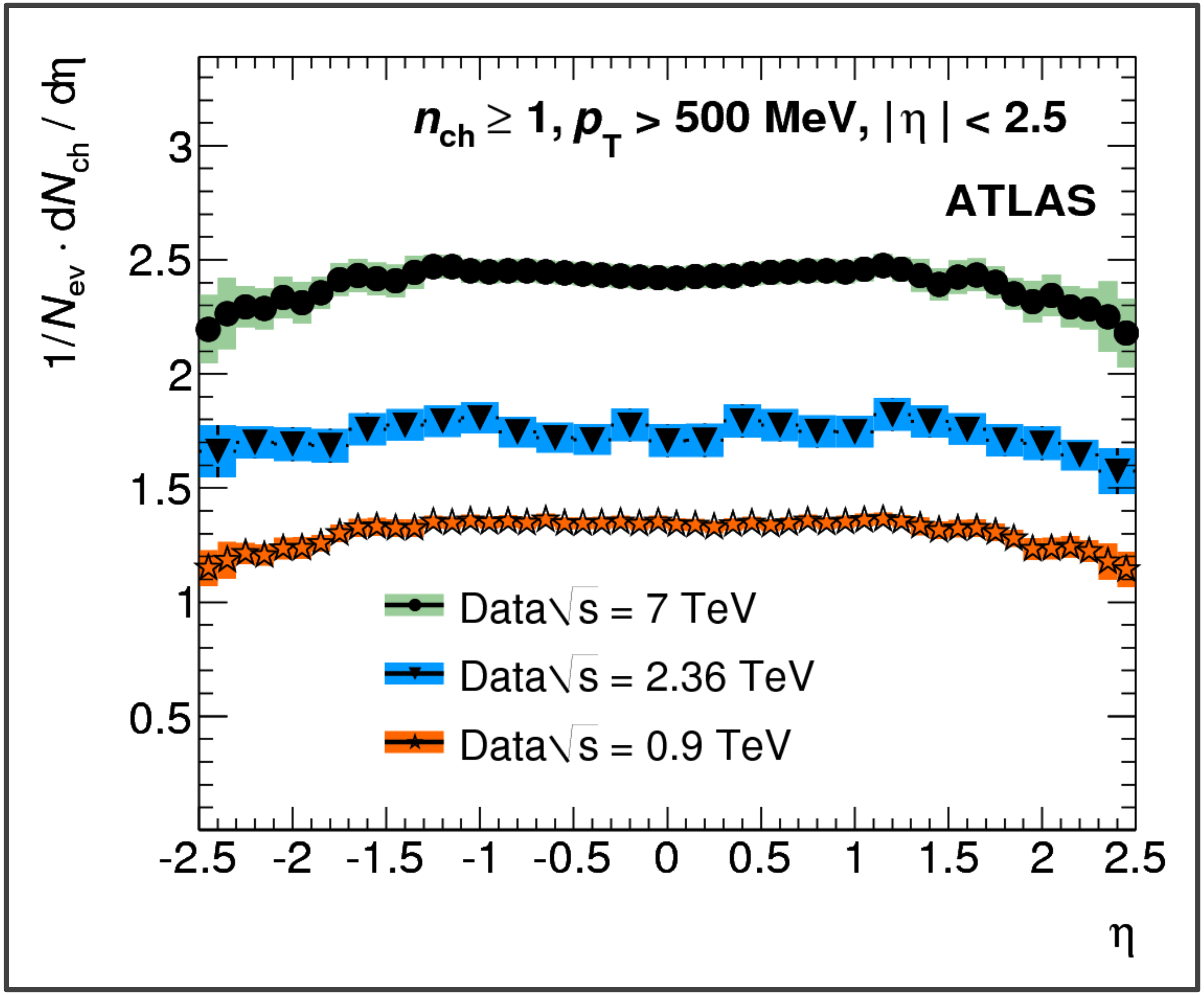
lower pT particles

particle multiplicity





Results at 0.9, 2.36 and 7 TeV

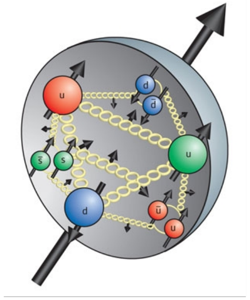


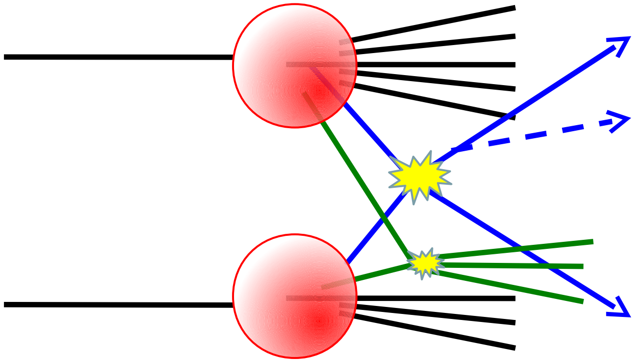
Higher energy ➘ probing more partons

1. Minimum Bias
2. **Underlying Event**
3. Total cross-section
4. Diffractive cross-sections
5. Particle Correlations

Reminder : Underlying Event

Soft-QCD processes also occur in the same proton-proton interaction as a (more interesting) hard interaction:





Multiple Parton Interactions (MPI)

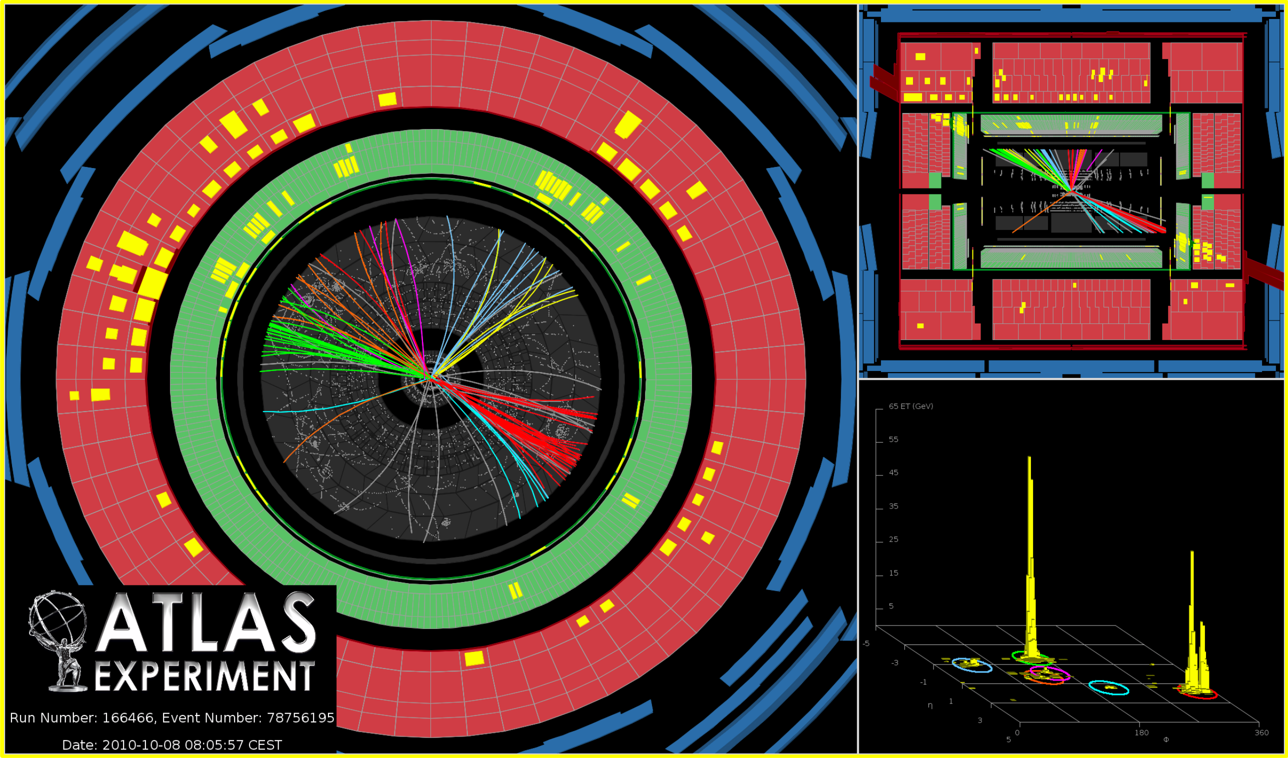
The Underlying Event (UE) is everything not associated with the hard parton-parton interaction

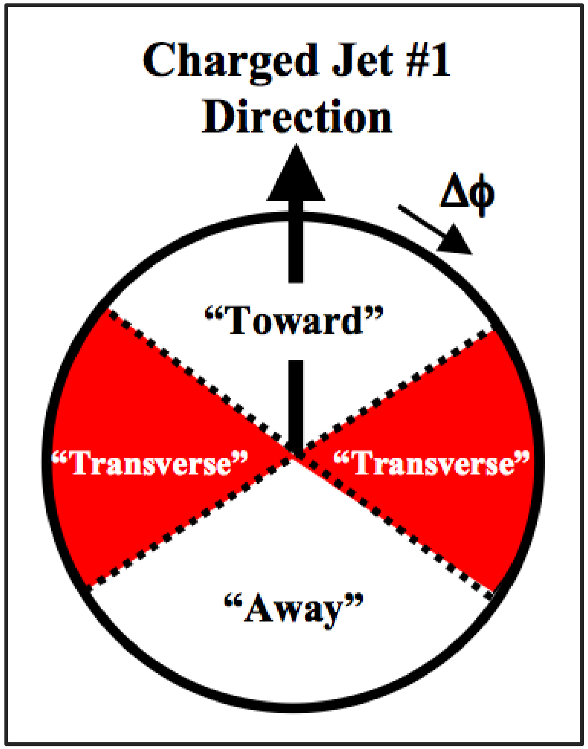
Underlying Event Measurements

How can we make measurements of the particle activity from the Underlying Event ?

Simple technique pioneered by CDF during Tevatron Run I

e.g. in di-jets : the activity from the hard parton-parton interaction produces two back-to-back jets (in the transverse plane)





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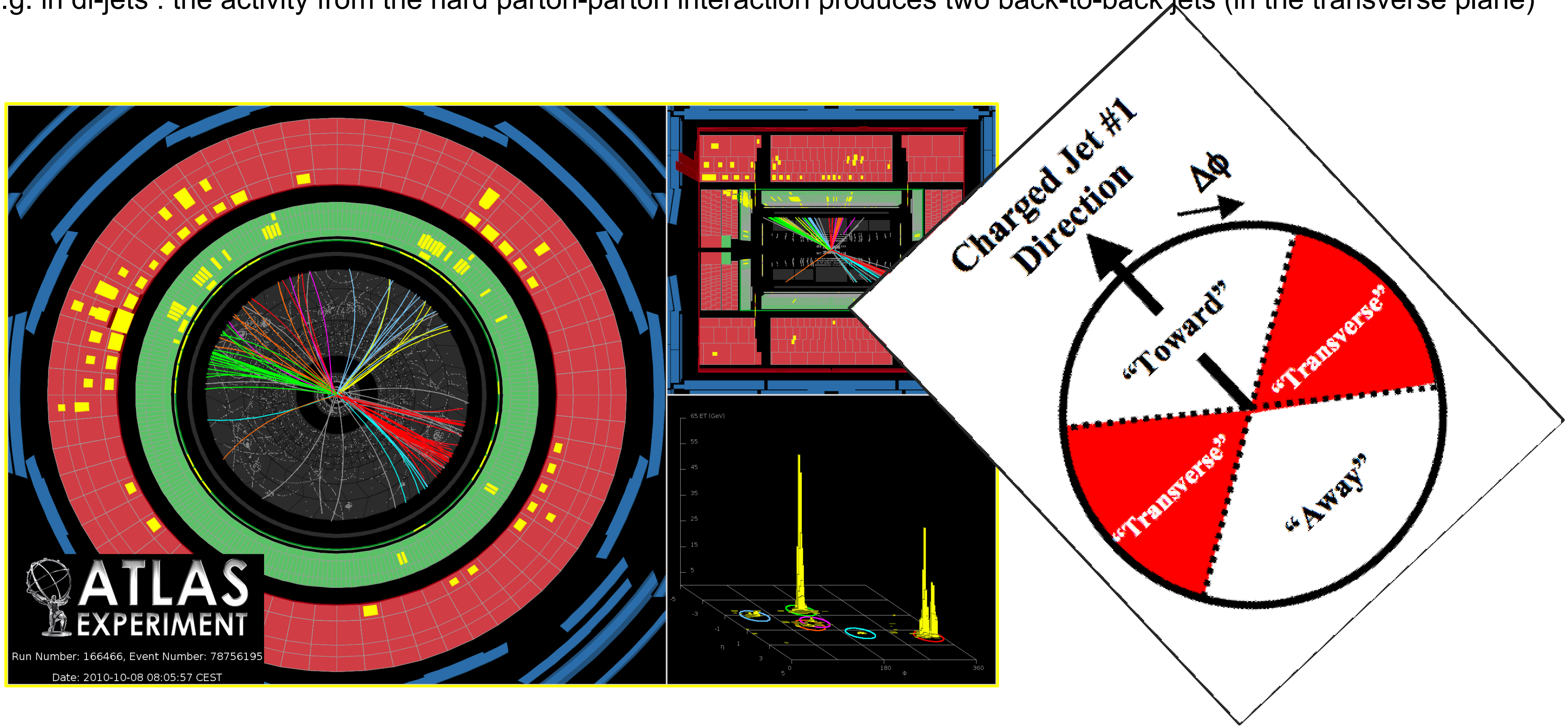
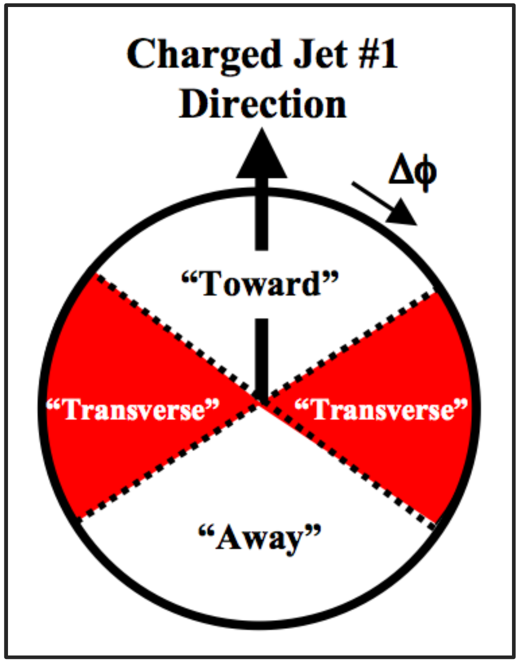
Simple technique pioneered by CDF during Tevatron Run I

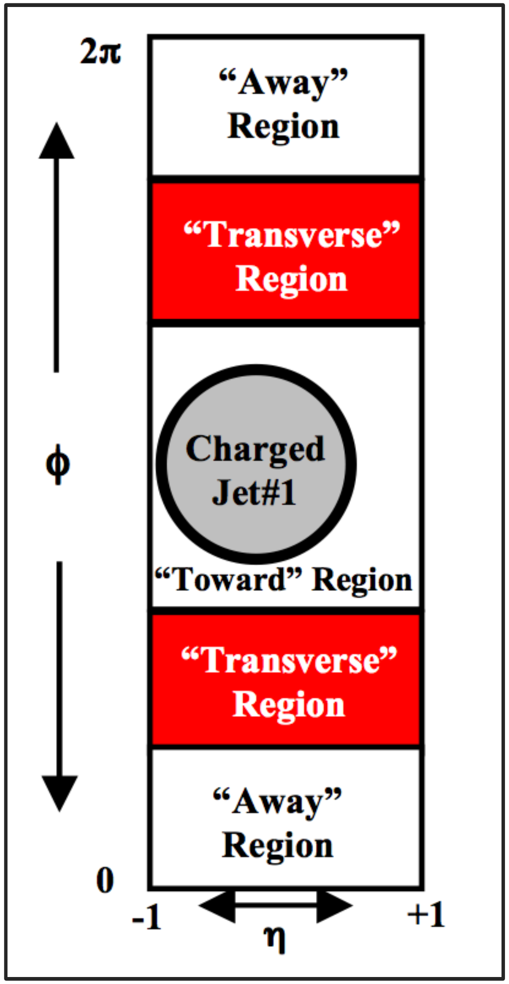
e.g. in di-jets : the activity from the hard parton-parton interaction produces two back-to-back jets (in the transverse plane)



Underlying Event Measurements

60° < |ΔΦ| < 120°

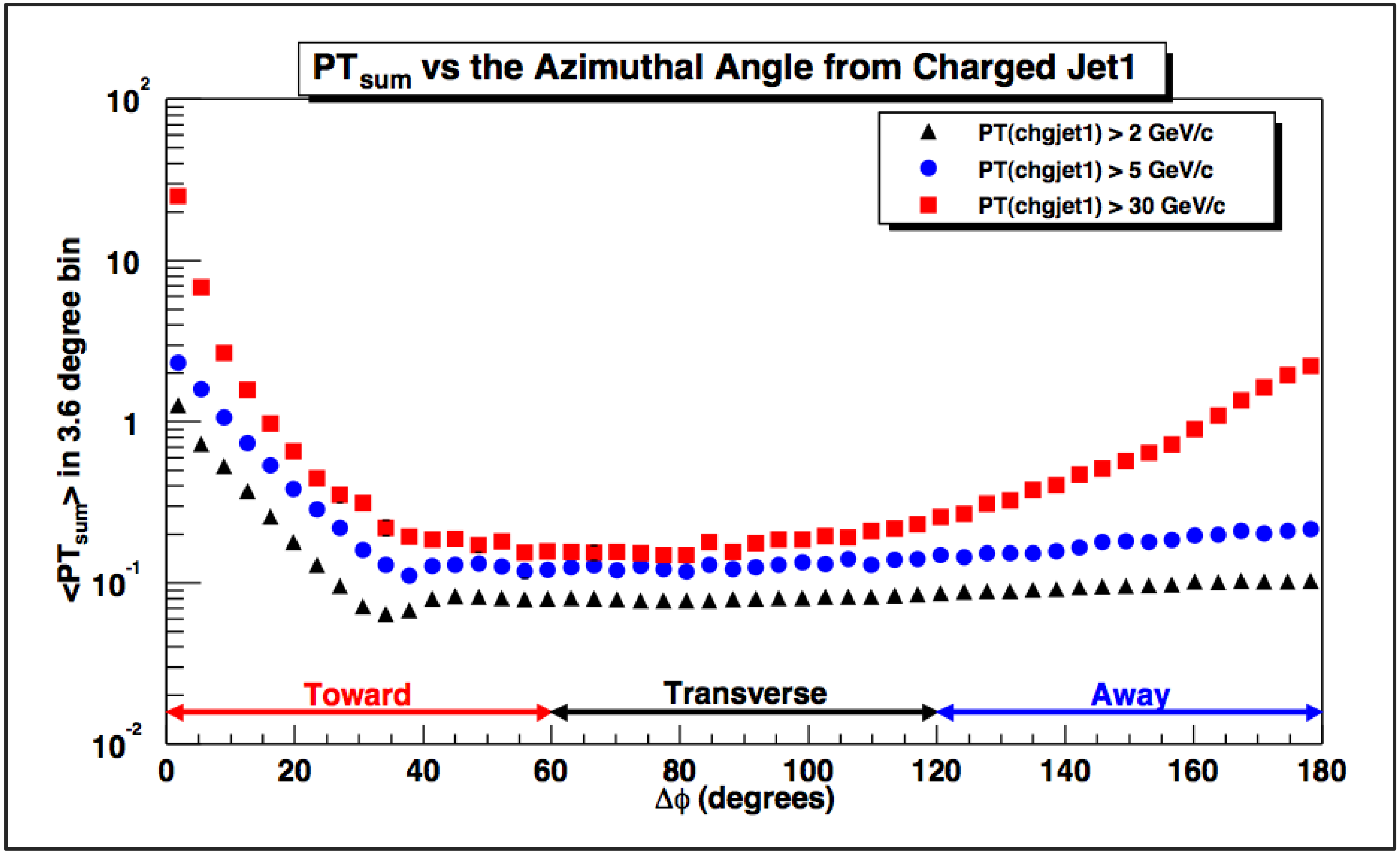


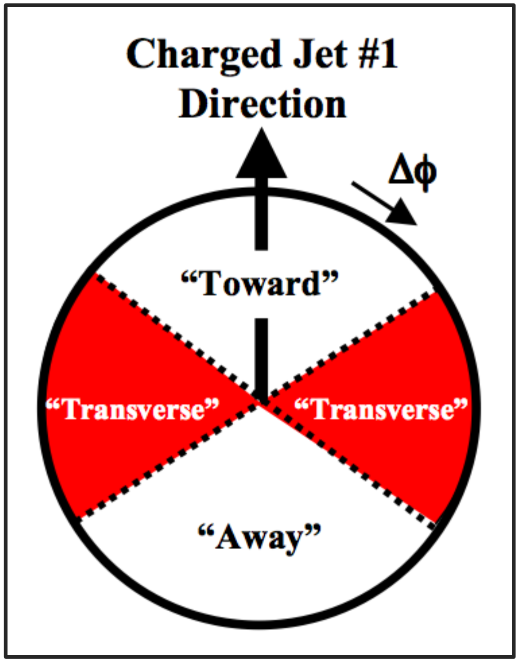


Define the direction of the "hard scatter" (highest pT jet /particle)

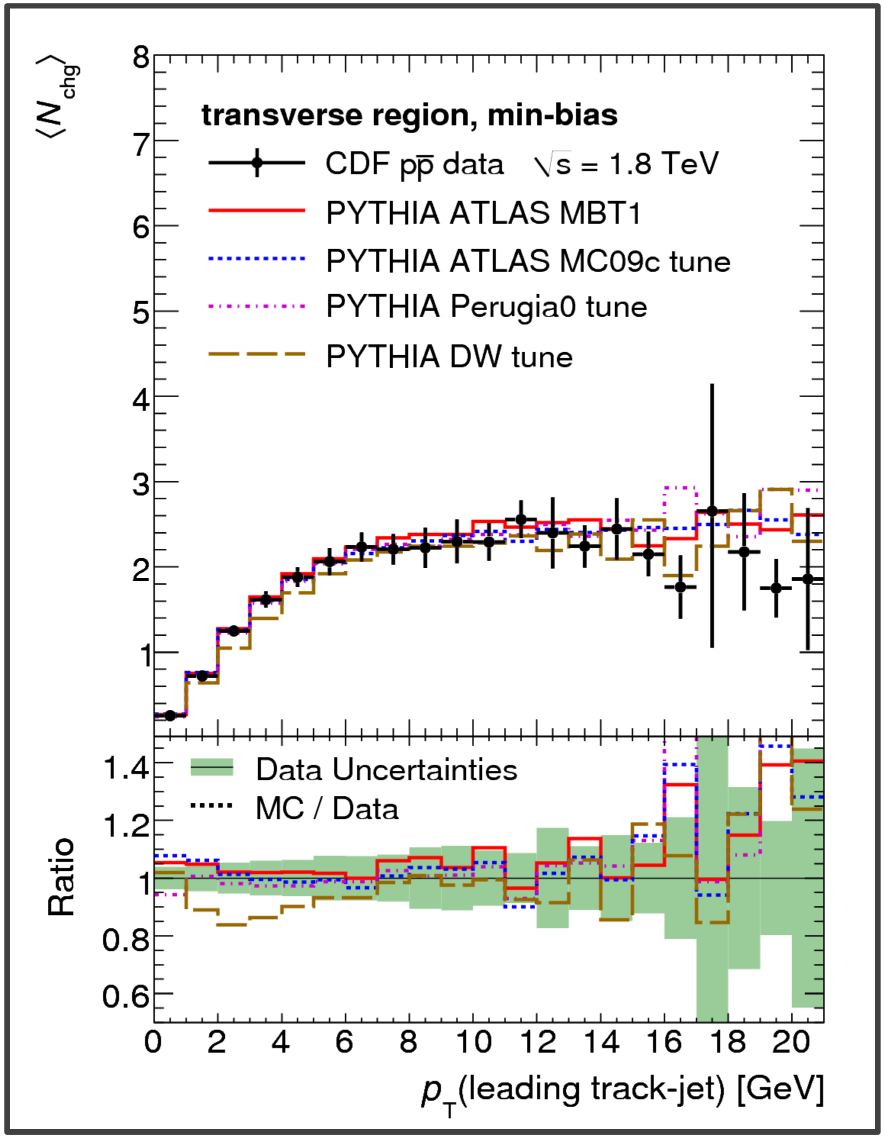
Study the activity (# of particles or ΣpT) in the region "transverse" to the hard scatter

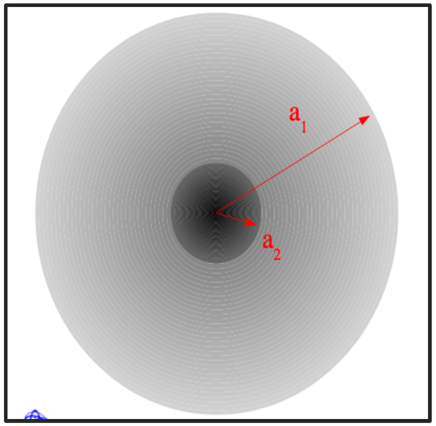
Underlying Event Measurements





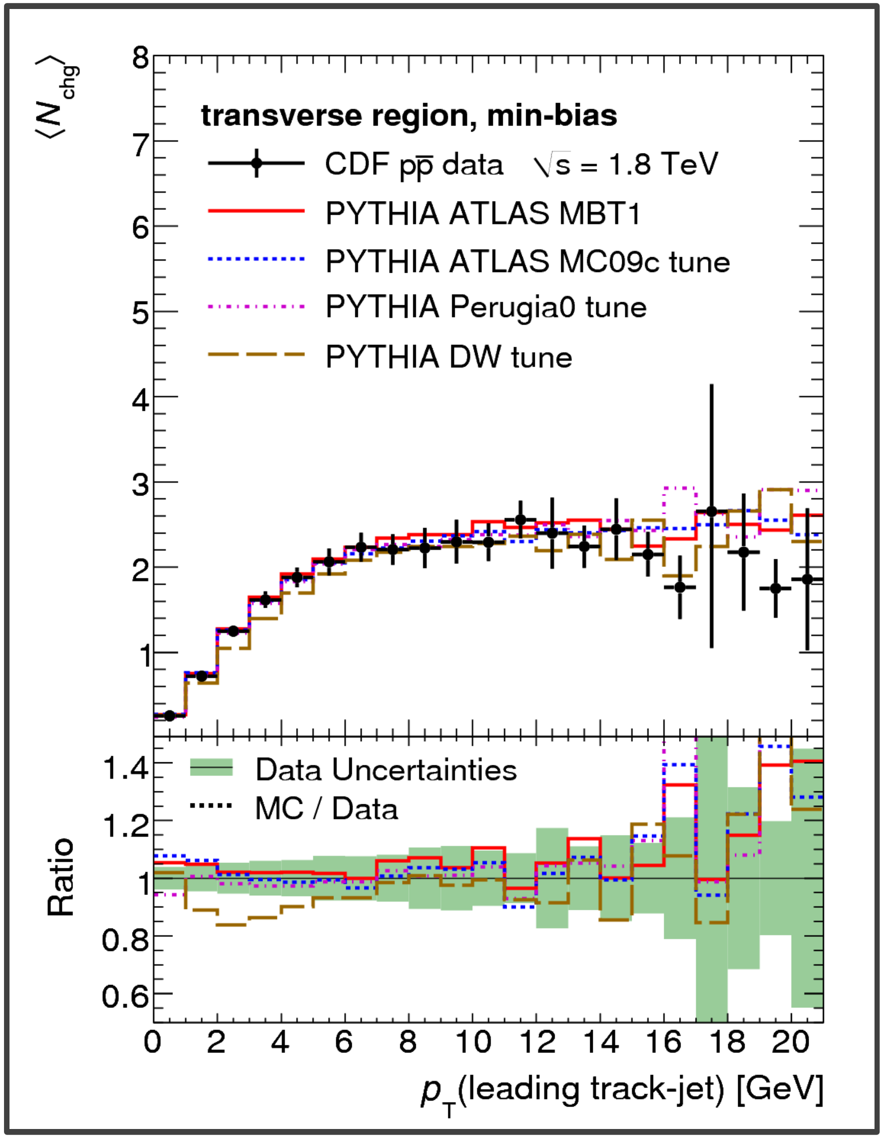
Underlying Event Measurements

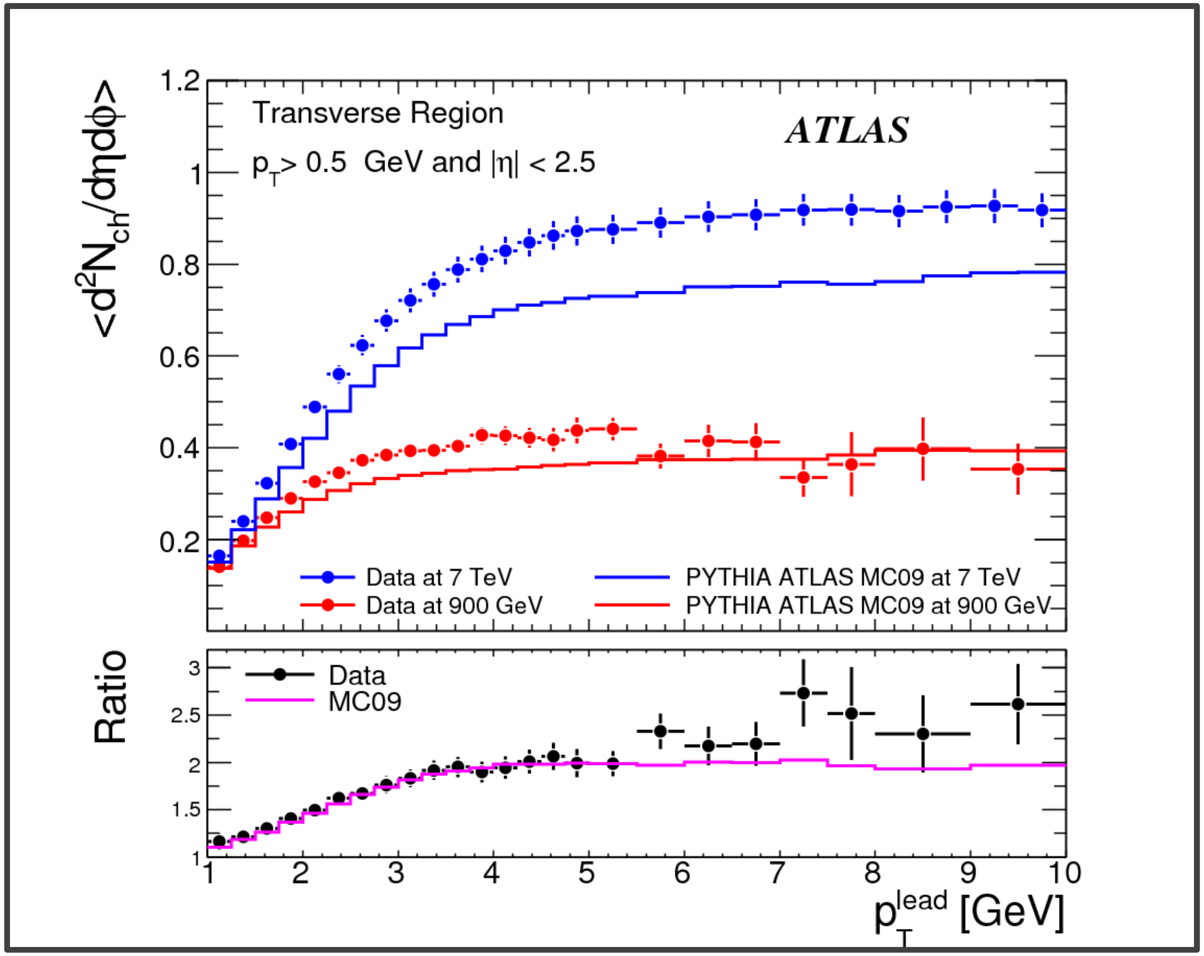




Proton matter distribution

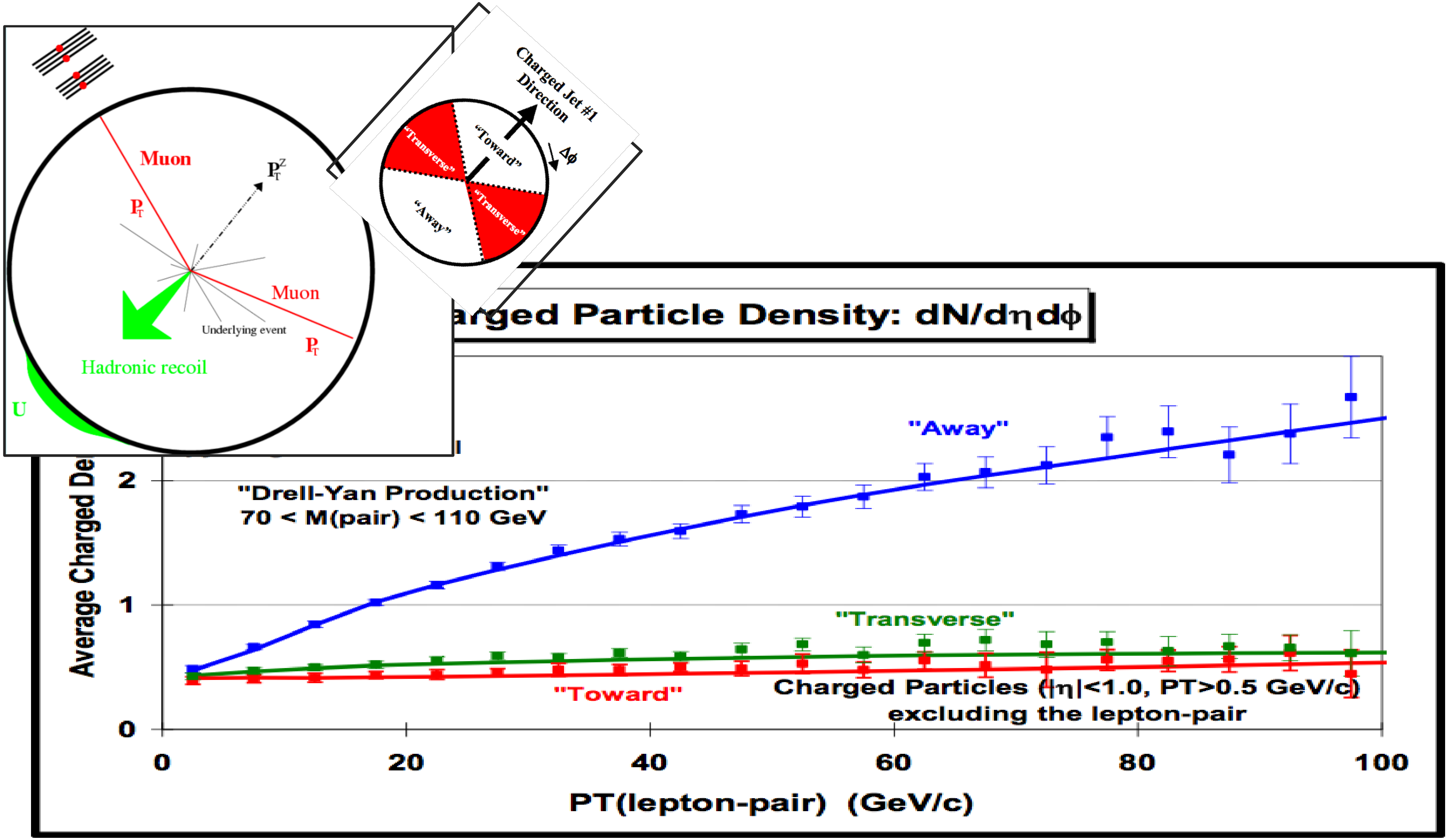
Underlying Event Measurements





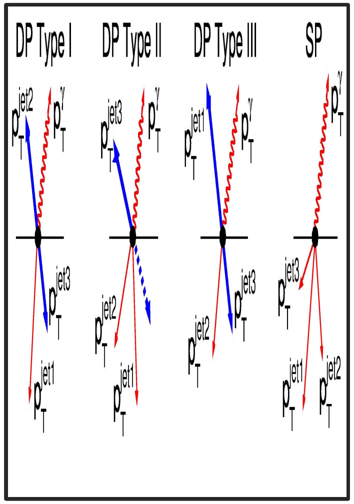
Inconsistency between LHC and Tevatron results?
Currently analysing 2.76 TeV LHC and 0.9 TeV Tevatron data to resolve the issue

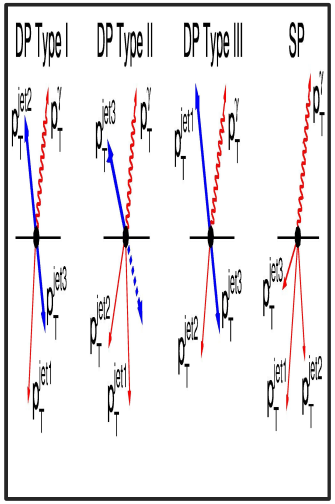
Underlying Event in Z->ℓℓ

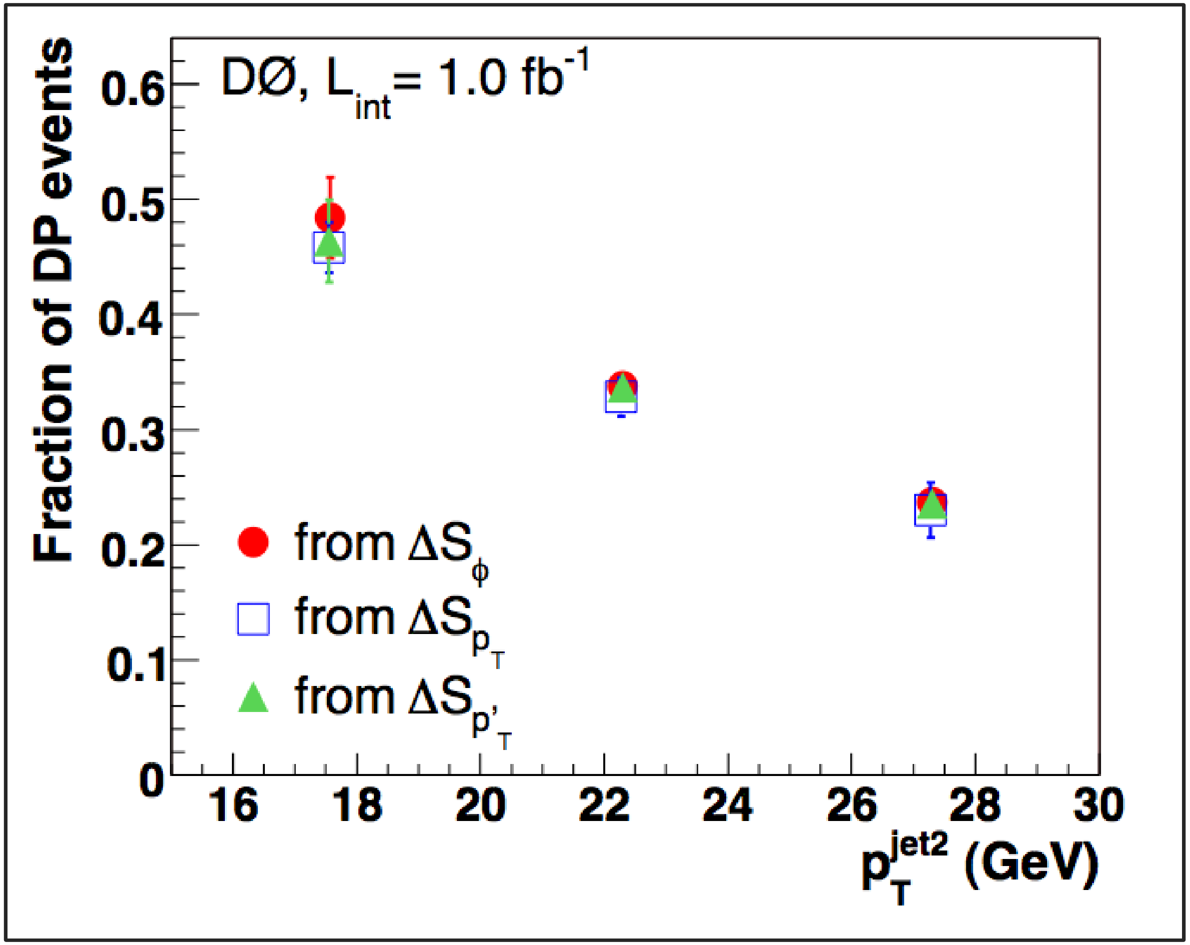


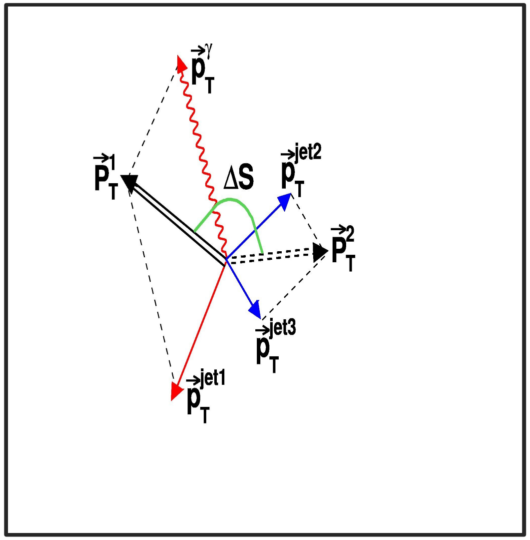
Double parton scattering

The high pT tails of the Underlying Event… (not really soft-QCD anymore)



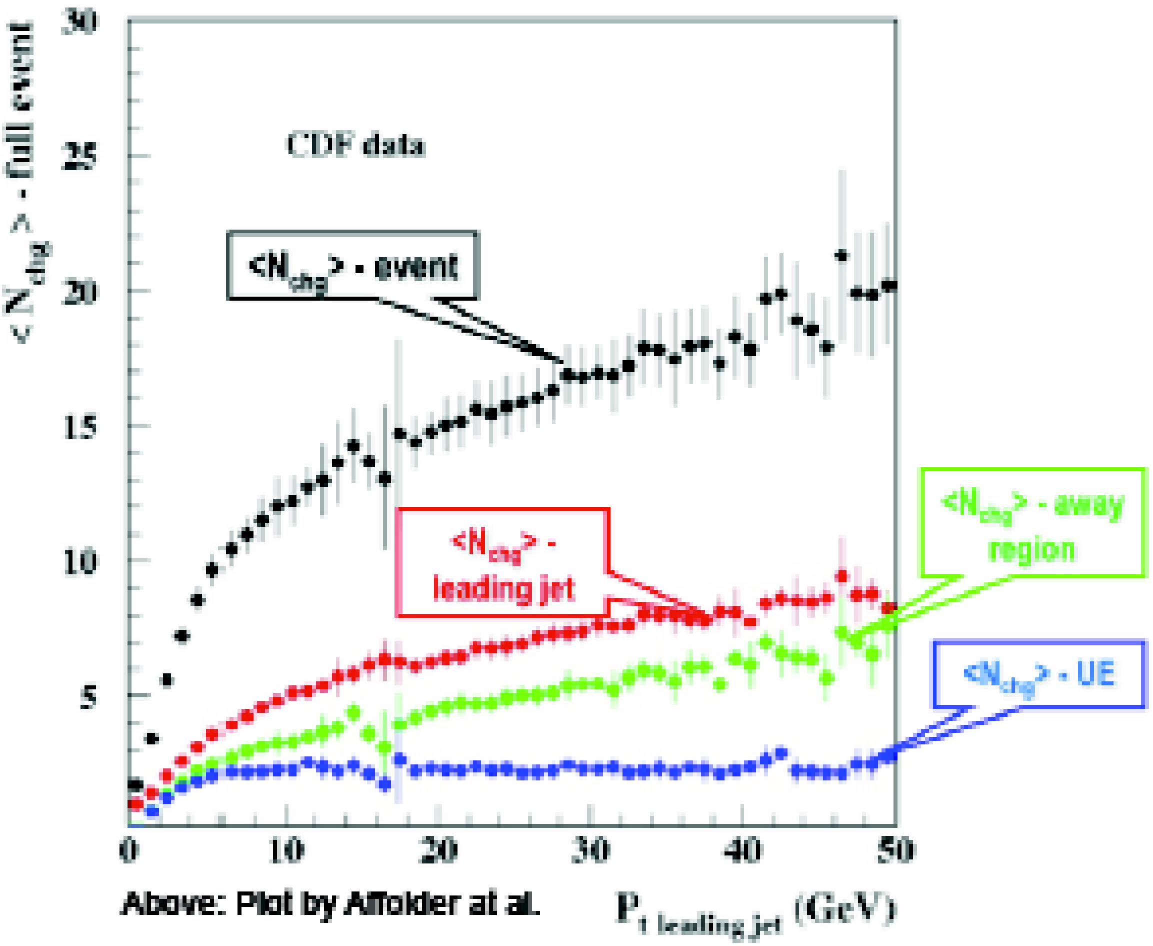




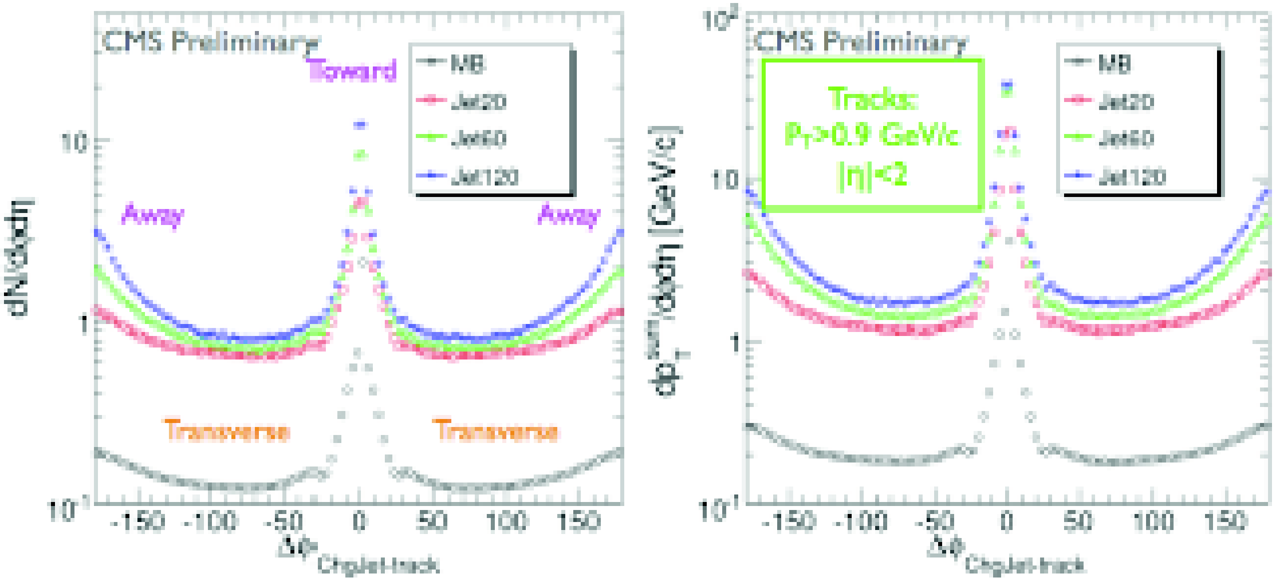


UE Characterization

- The number of tracks in the transverse region is less correlated to the lead jet energy.
- Sources of transverse tracks:
  - MPI
  - Fragmentation of string connections to remnants.
- Track Jets are used, so that low energy calorimeter response is not involved.
  - Also simplifies comparison to models.
- Drell-Yan: Look for $\mu^+\mu^-$ there is no FSR associated with their production.
  - The entire φ range characterizes the UE.

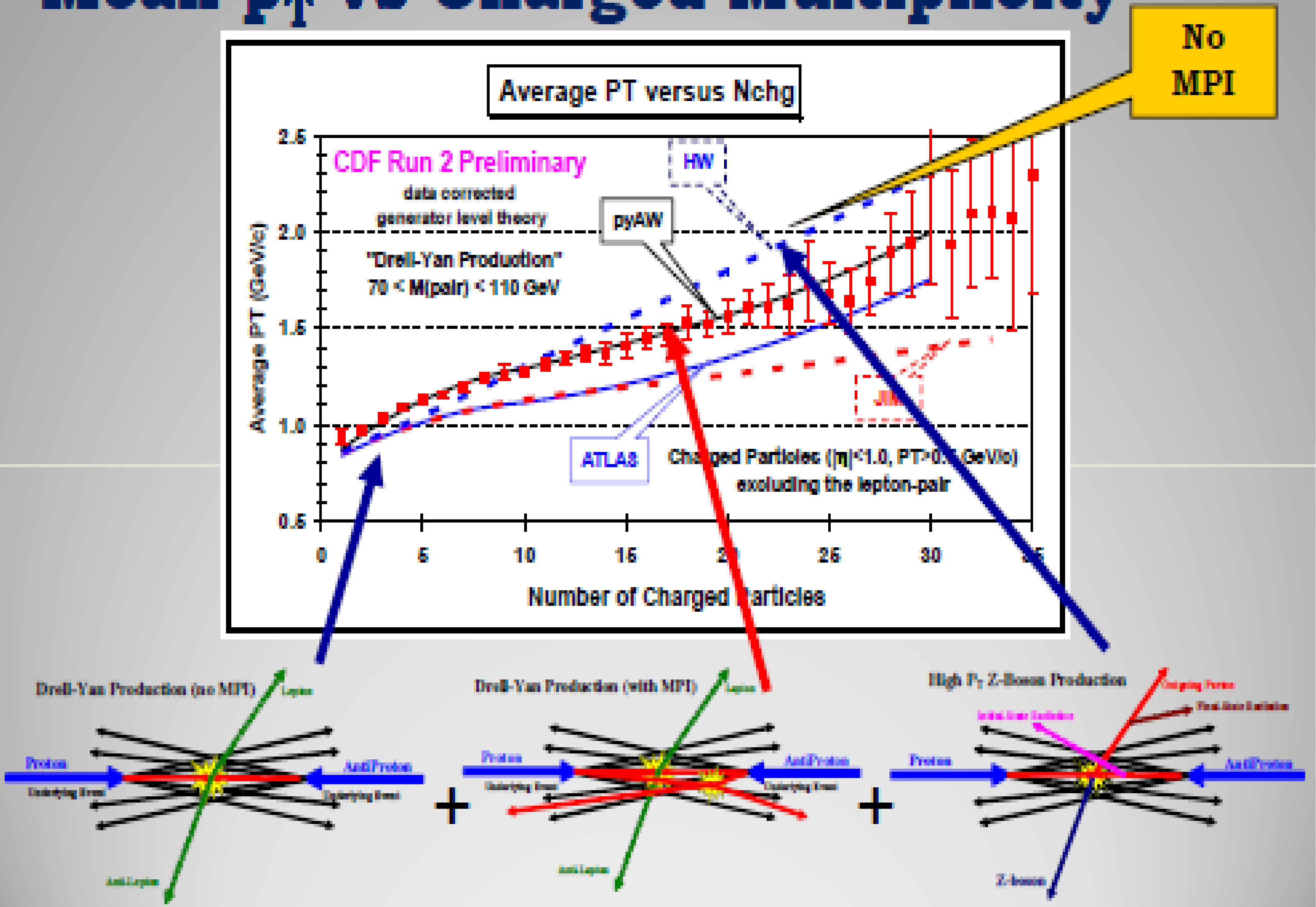


Above: Plot by Affolder at al.



Above: Plots from F. Ambroglini

Mean p_T vs Charged Multiplicity

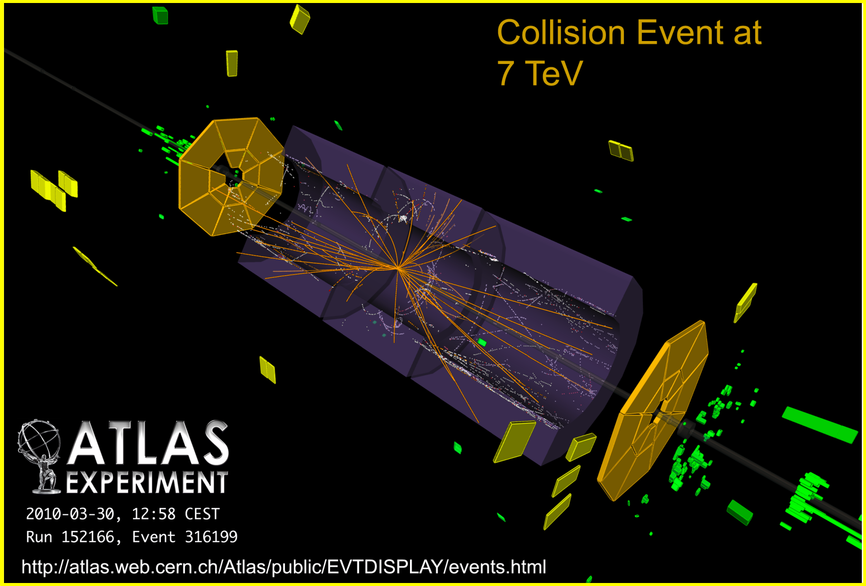


1. Minimum Bias
2. Underlying Event
3. **Total cross-section**
4. Diffractive cross-sections
5. Particle Correlations

Inelastic cross-section measurement

$$\sigma_{inel} = \frac{Nevts - Nbck}{\varepsilon \times \mathcal{L}}$$

1. Nevts : count inelastic collisions
2. ε : Correct for detector efficiency
3. $\mathcal{L}$: Normalise with luminosity



Minimum Bias Trigger Scintillators :
2.09 < |η| < 3.84

Nevts = # events with ≥ 2 counters above threshold

σinel (ξ > 5×10-6) = 60.3 ± 0.05(stat) ± 0.5(syst) ± 2.1(lumi) mb

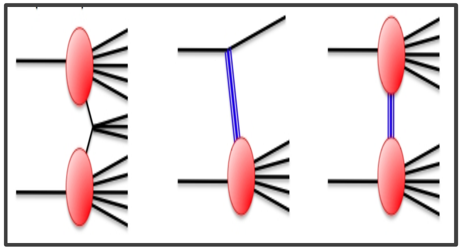
Measurement restricted to region in which we are sensitive (e.g. at least one charged particle with |η| < 3.84)

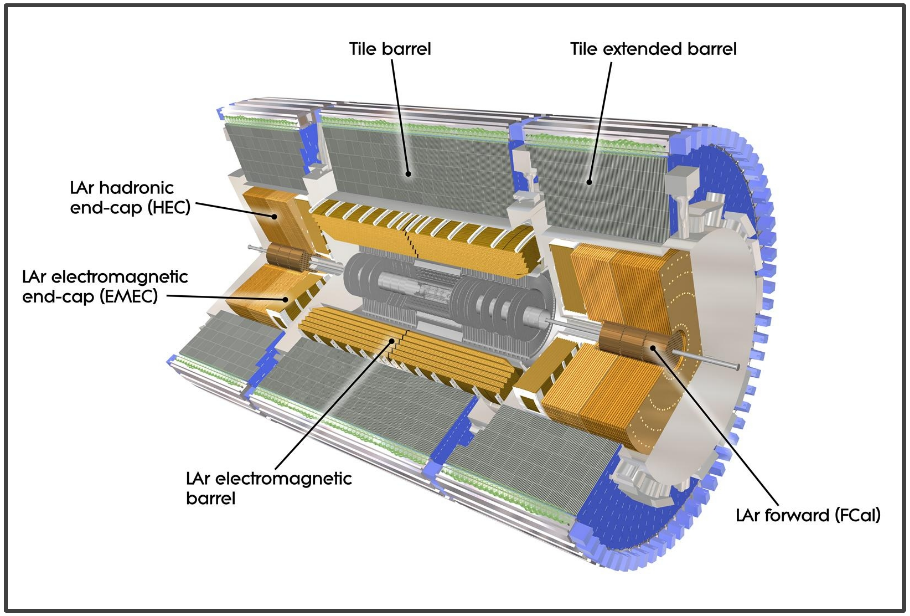
1. Minimum Bias
2. Underlying Event
3. Total cross-section
4. **Diffractive cross-sections**
5. Particle Correlations

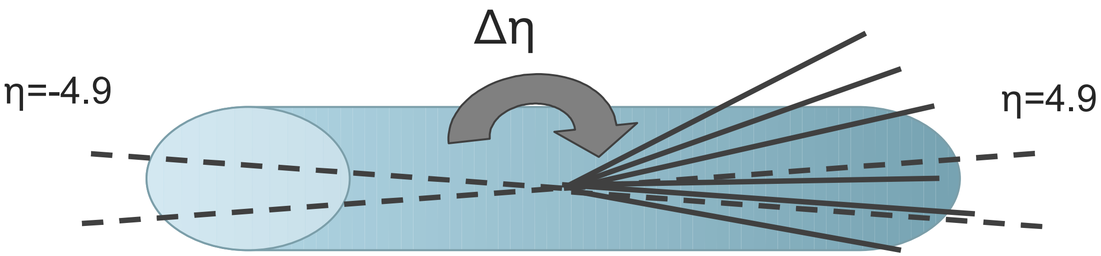
Gap cross-section

Diffractive events tend to have large “rapidity gaps”

Measure σ vs Δη (large Δη dominated by diffraction)

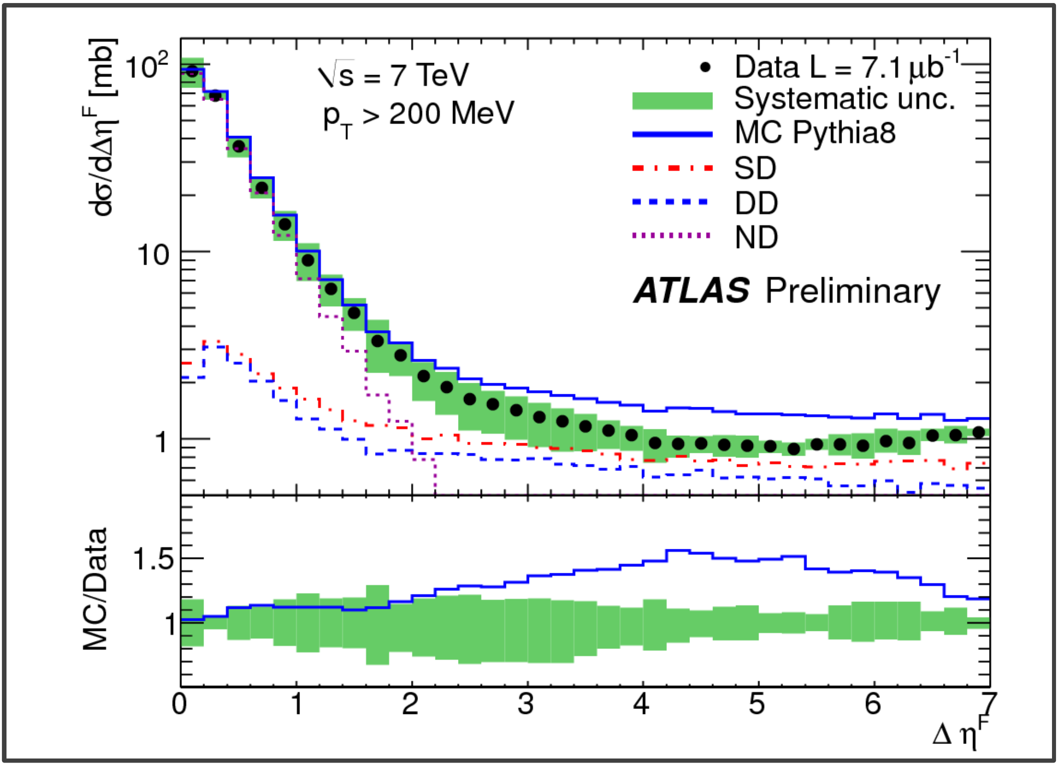


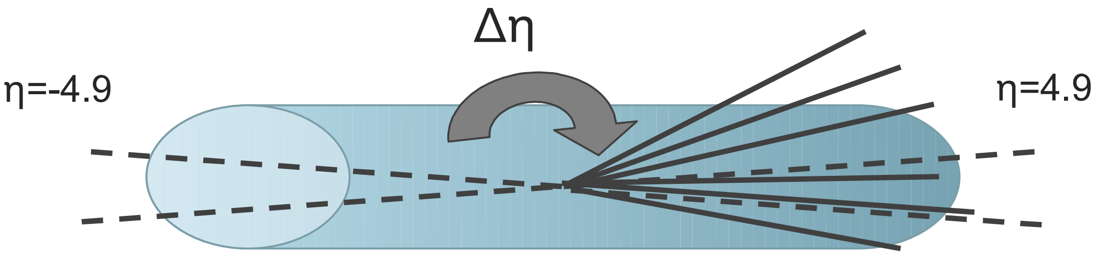




Calorimeters : |η| < 4.9
Inner Tracking Detector : |η| < 2.5

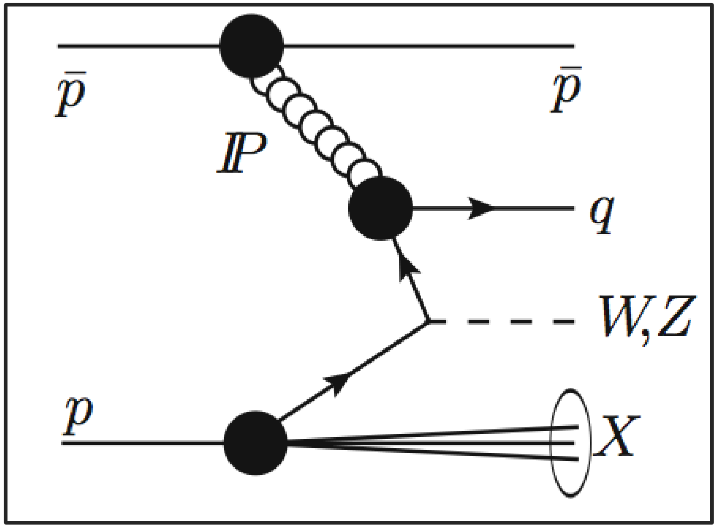
Gap cross-section

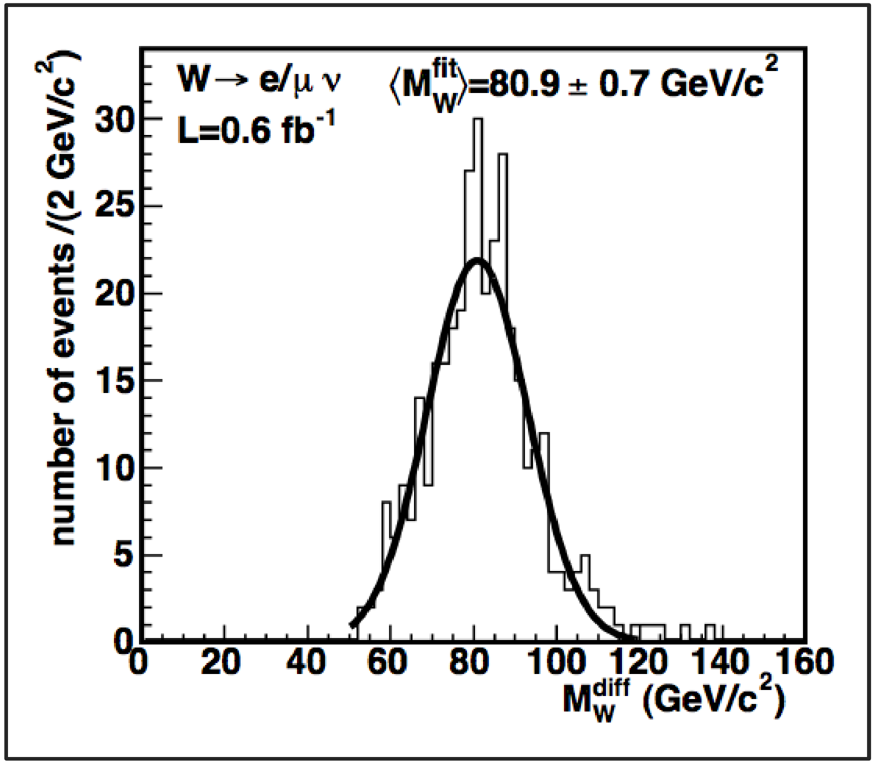


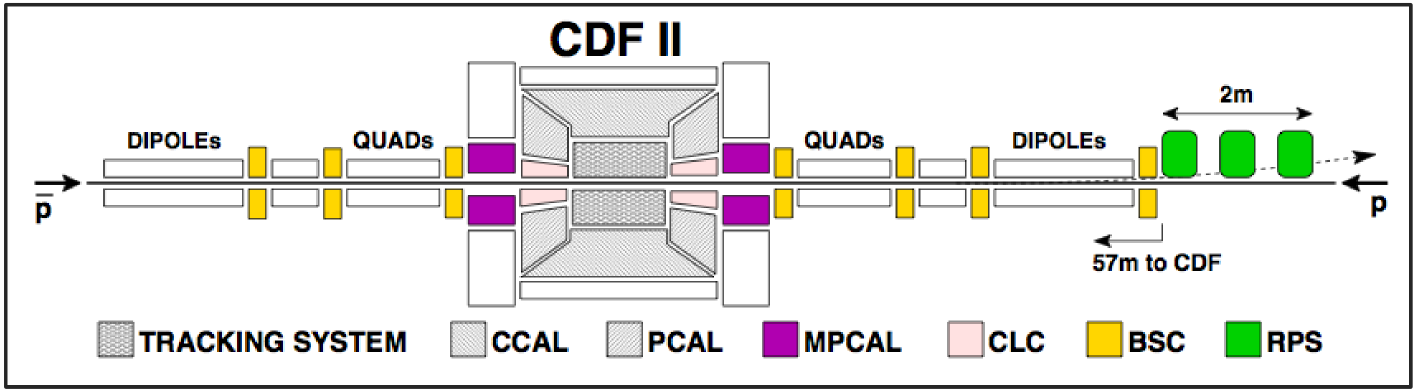


Other diffractive processes

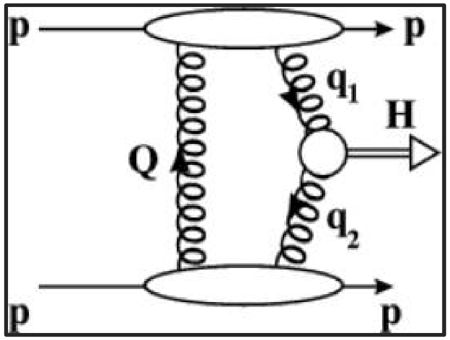
Not really soft-QCD anymore….





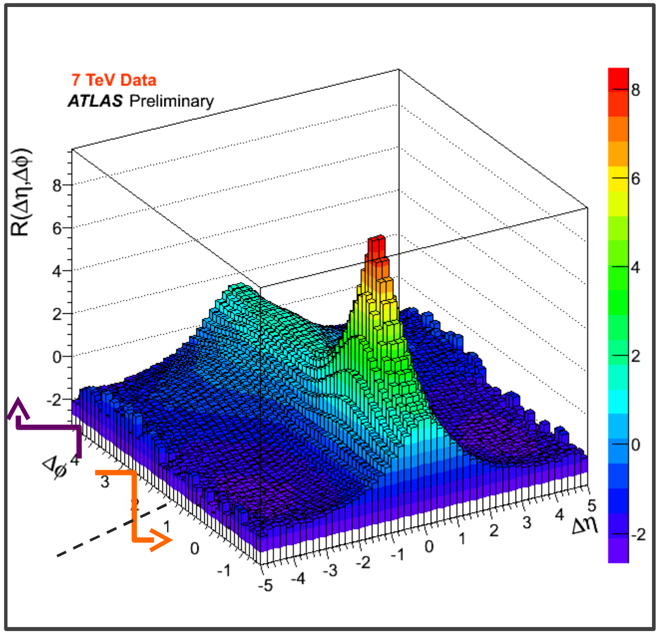


Higgs?



1. Minimum Bias
2. Underlying Event
3. Total cross-section
4. Diffractive cross-sections
5. **Particle Correlations**

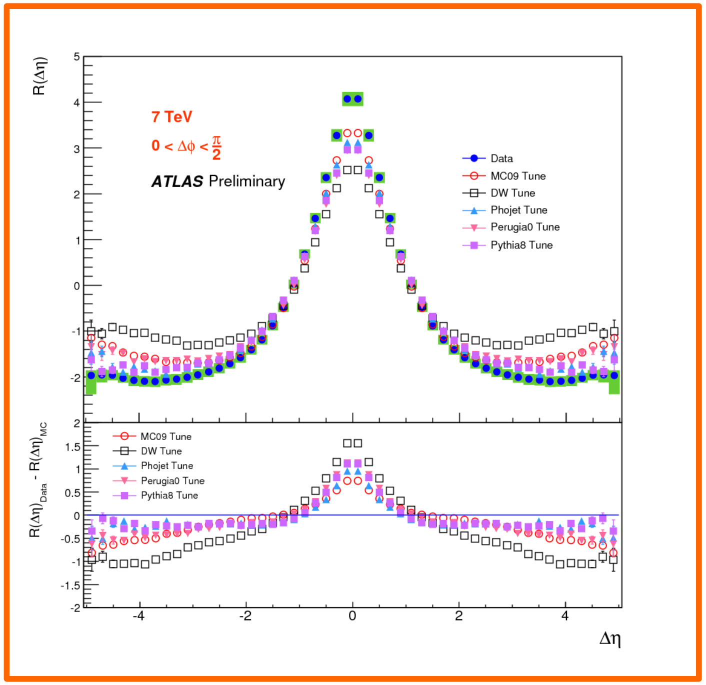
Two particle correlations

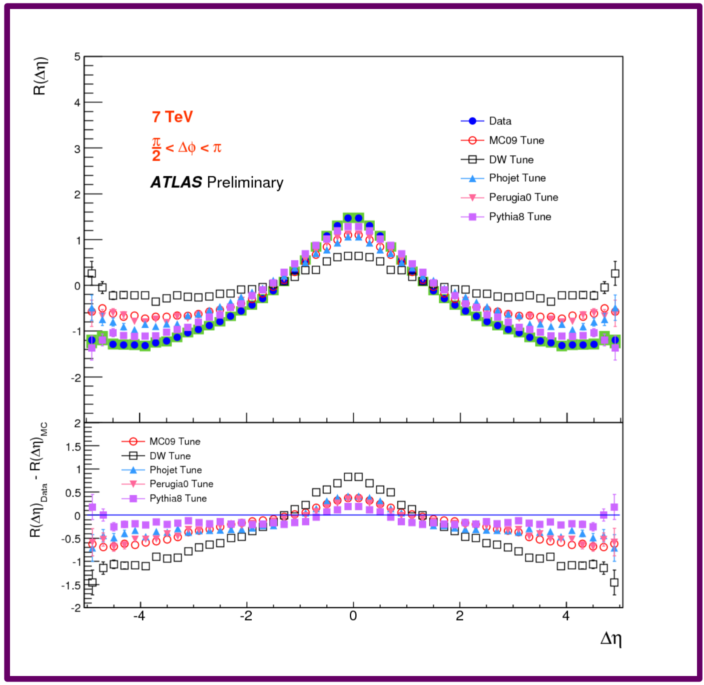


$R(\Delta\eta,\Delta\Phi) = (F(\Delta\eta,\Delta\Phi) - B(\Delta\eta,\Delta\Phi)) / B(\Delta\eta,\Delta\Phi)$ (+ normalisation factors)

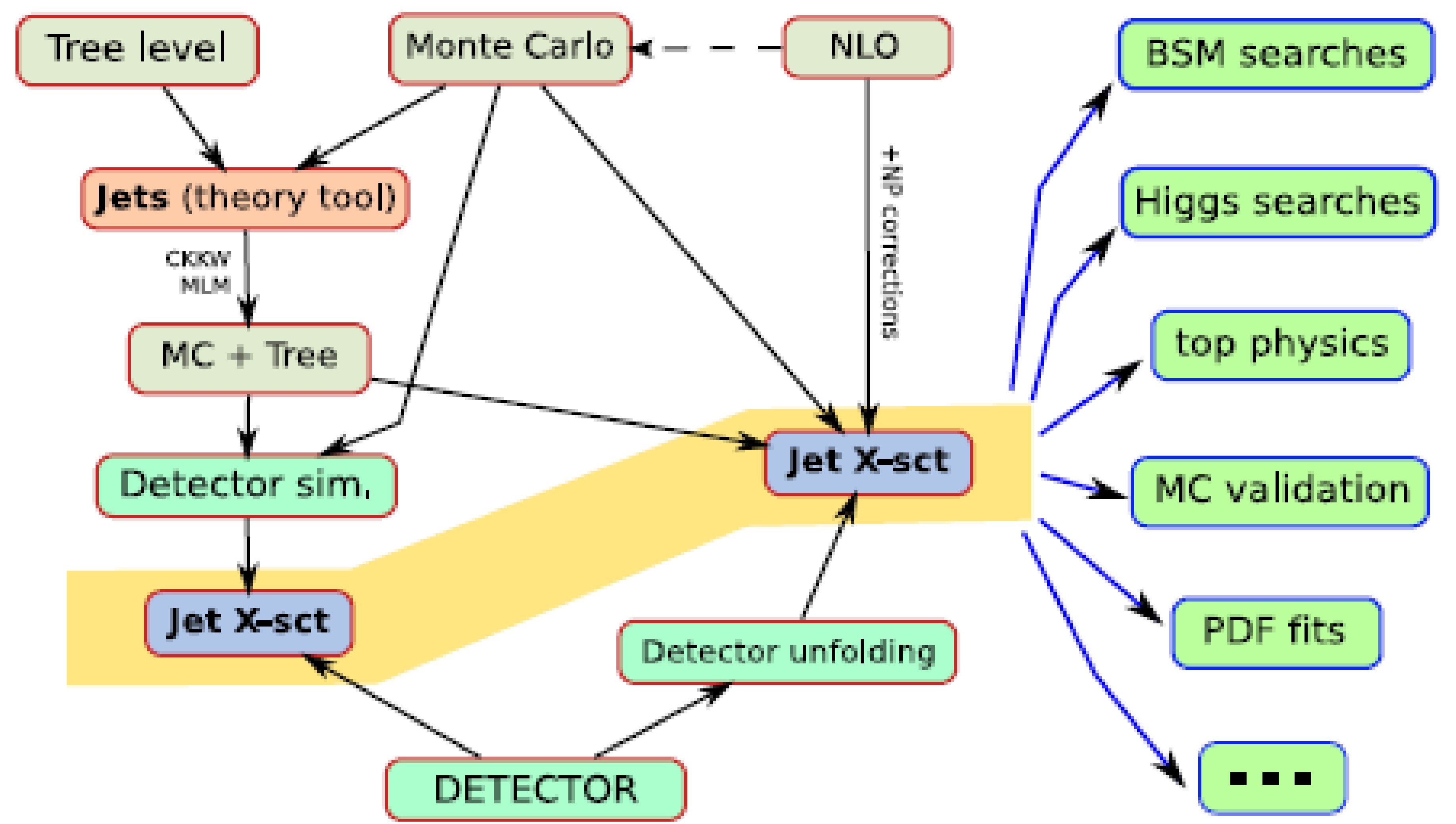
F : all particle pairs in same event
B : pair particles from different events

1D projections on Δη axis :
(ΔΦ projections not shown)





QCD and Jets



Jet (definitions) provide central link between expt., "theory" and theory

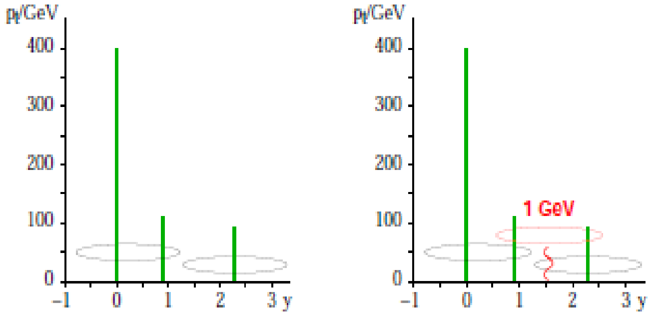
And jets are an input to almost all analyses

Two types of jet finders

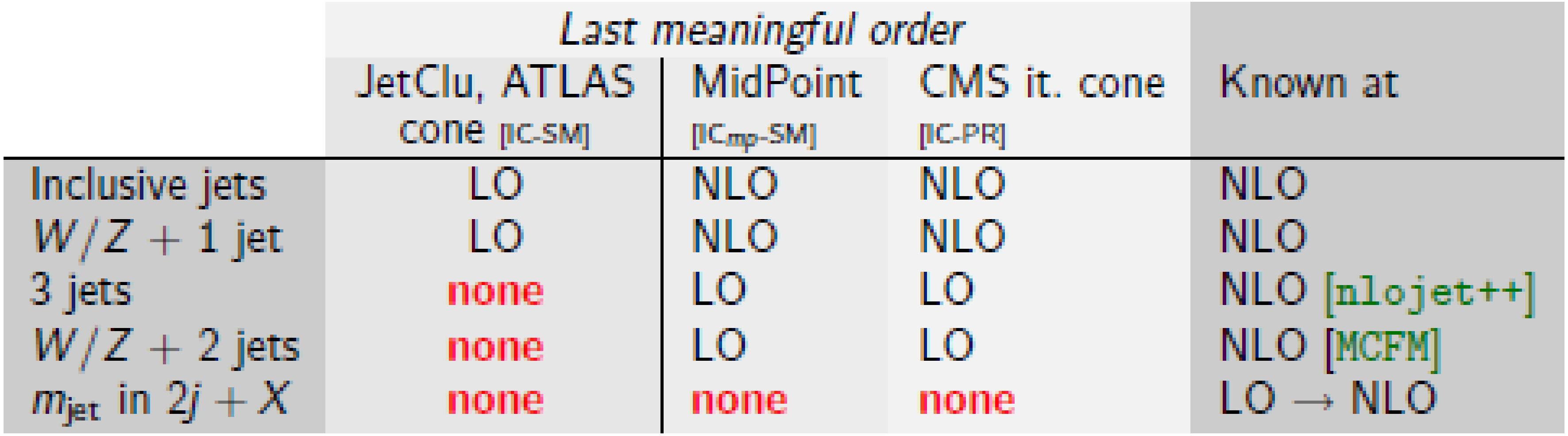
- Cone algorithms:
  - start with a high-Pt deposition, then take everything with distance smaller than a given radius in (η,ϕ) space
  - ex. JetClu, Atlas cone, CMS cone, MidPoint, PxCone, SISCone
- Iterative recombination:
  - Merge nearby clusters, and combine them into a single one; continue until can't find any more 'super clusters' close enough
  - ex. Kt, Anti-kt, Cambridge

Issues with cones

- Cone algorithms are apparently simple to understand and fast; but what happens if two cones overlap? Does the result depend on the choice of seed? (it shouldn't)

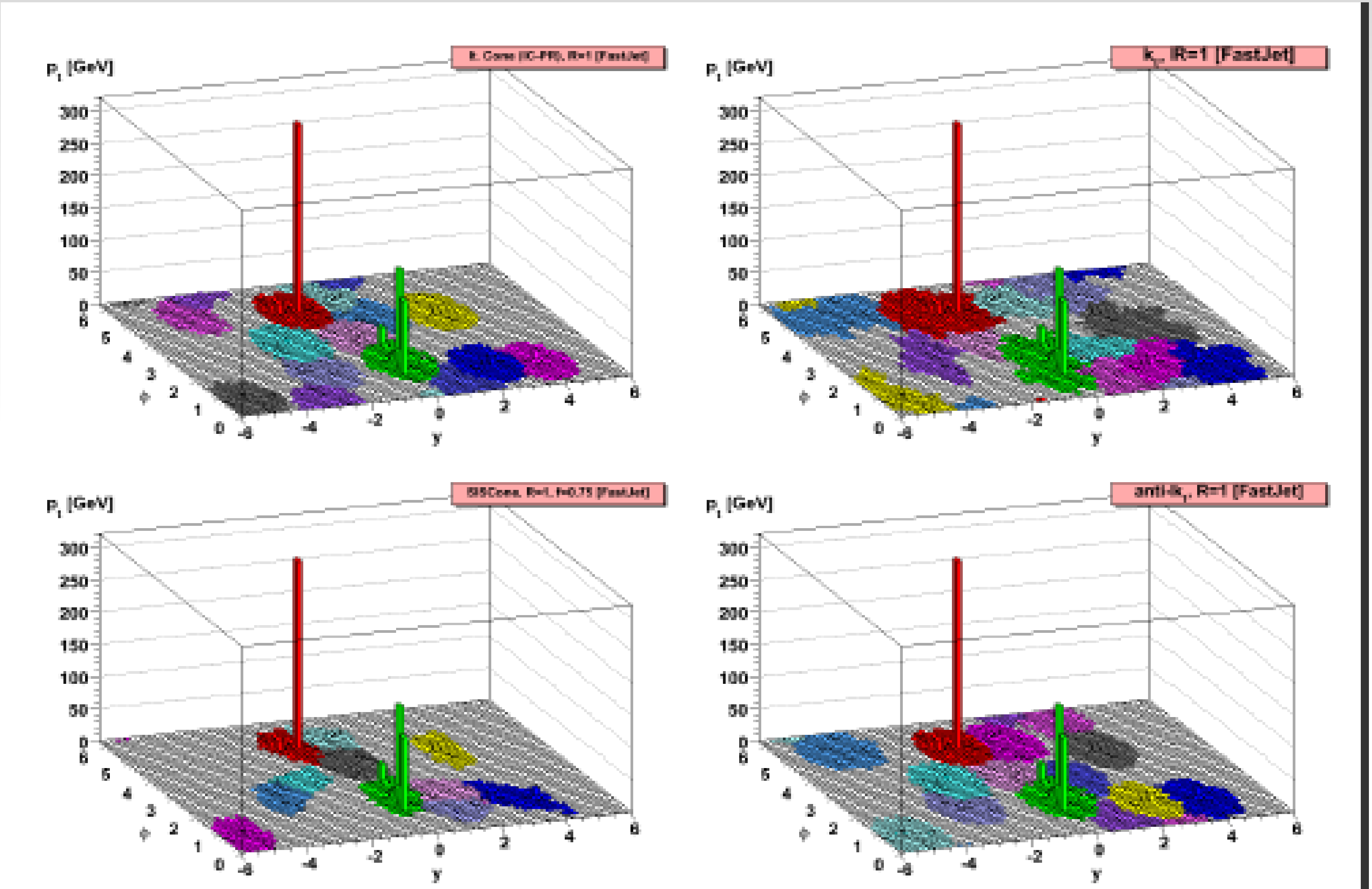


Stable cones with midpoint:	{1,2} & {3}	{1,2} & {2,3} & {3}
Jets with midpoint ($f = 0.5$)	{1,2} & {3}	{1,2,3}



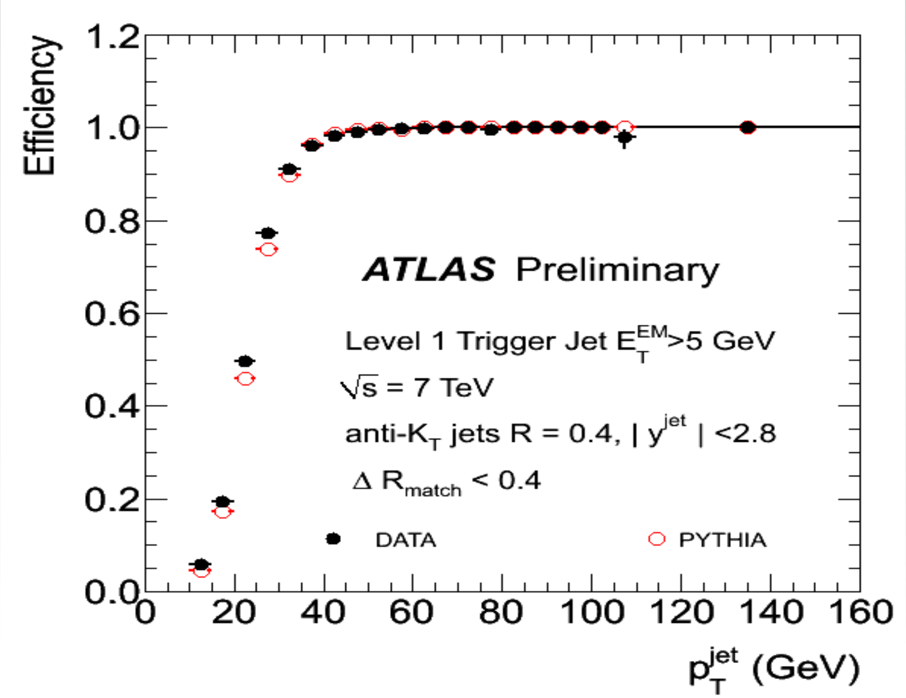
	Last meaningful order			
	JetClu, ATLAS cone [IC-SM]	MidPoint [IC$_{mp}$-SM]	CMS it. cone [IC-PR]	Known at
Inclusive jets	LO	NLO	NLO	NLO
$W/Z + 1$ jet	LO	NLO	NLO	NLO
3 jets	none	LO	LO	NLO [nlojet++]
$W/Z + 2$ jets	none	LO	LO	NLO [MCFM]
$m_{\rm jet}$ in $2j + X$	none	none	none	LO → NLO

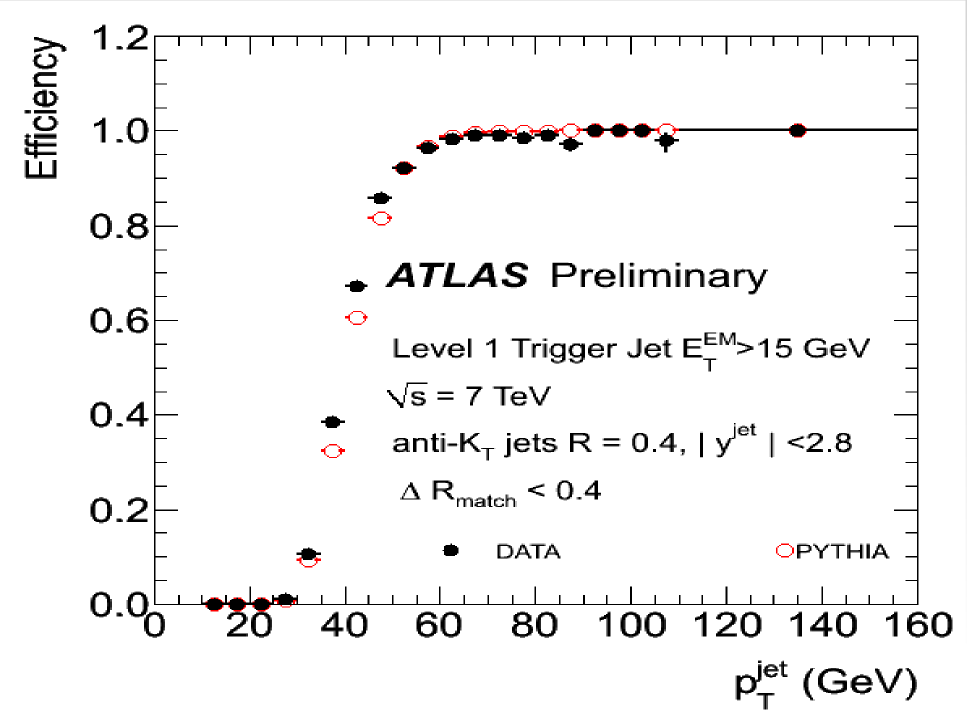
But the most conical cone is not a cone!



Anti-kt default algorithm in Atlas and CMS

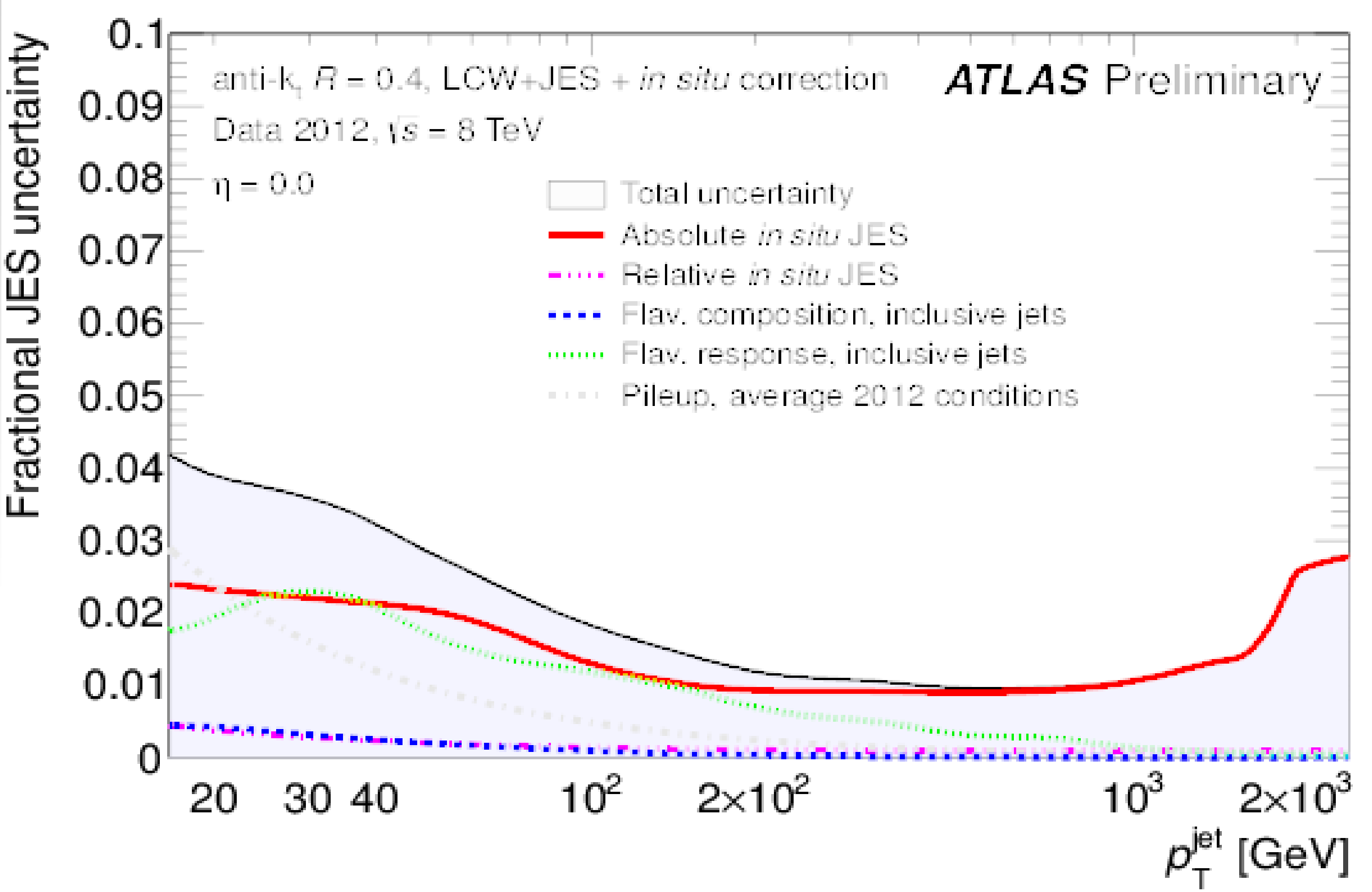
Measuring jet production: trigger





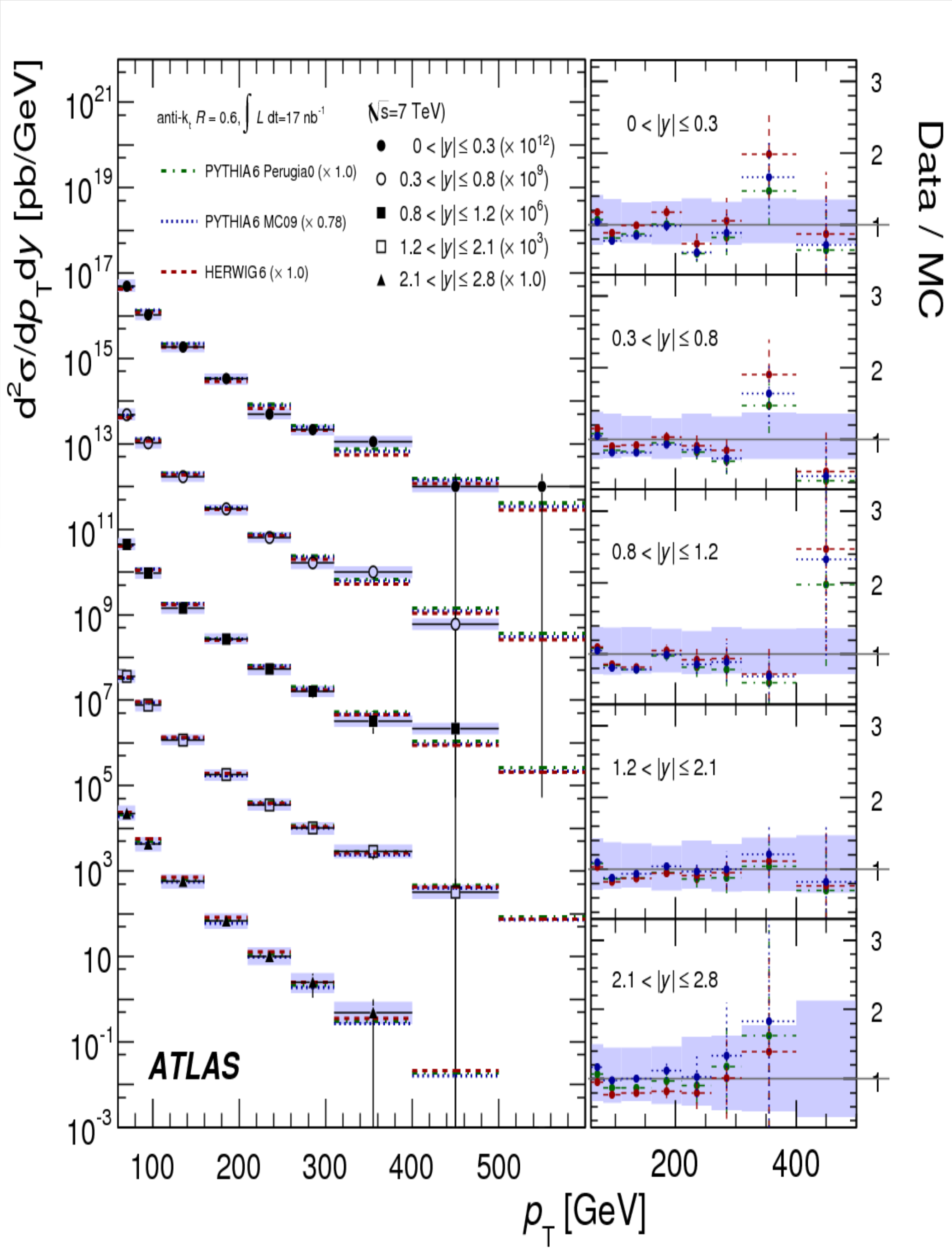
- Not to correct for the efficiency in the steeply rising part of the curve, jet cross section was first measured above the 100% efficiency point
- This results in the measurement being performed in different Pt bins in the various periods, because higher luminosities forced heavy prescales on lowest thresholds

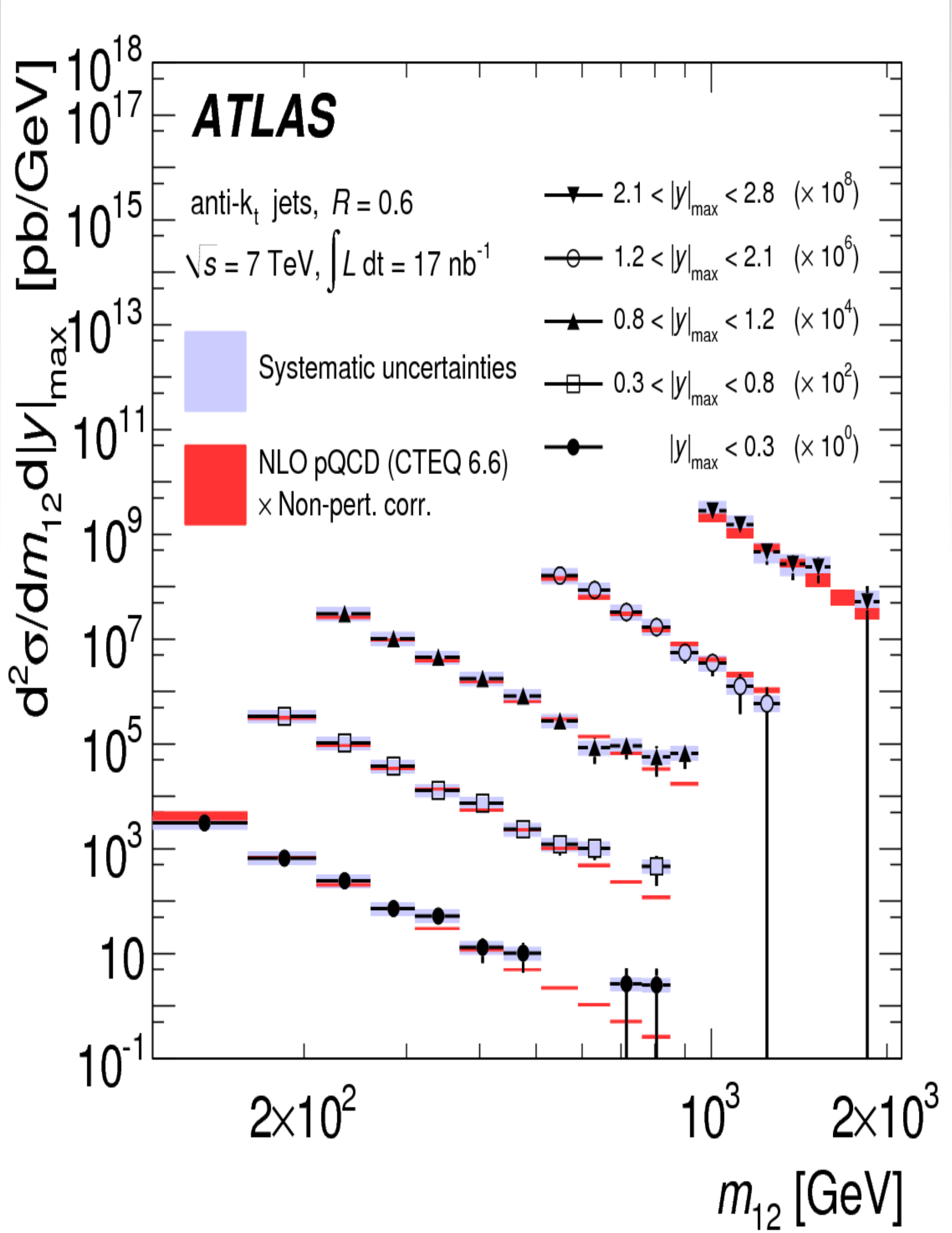
Jet Energy scale



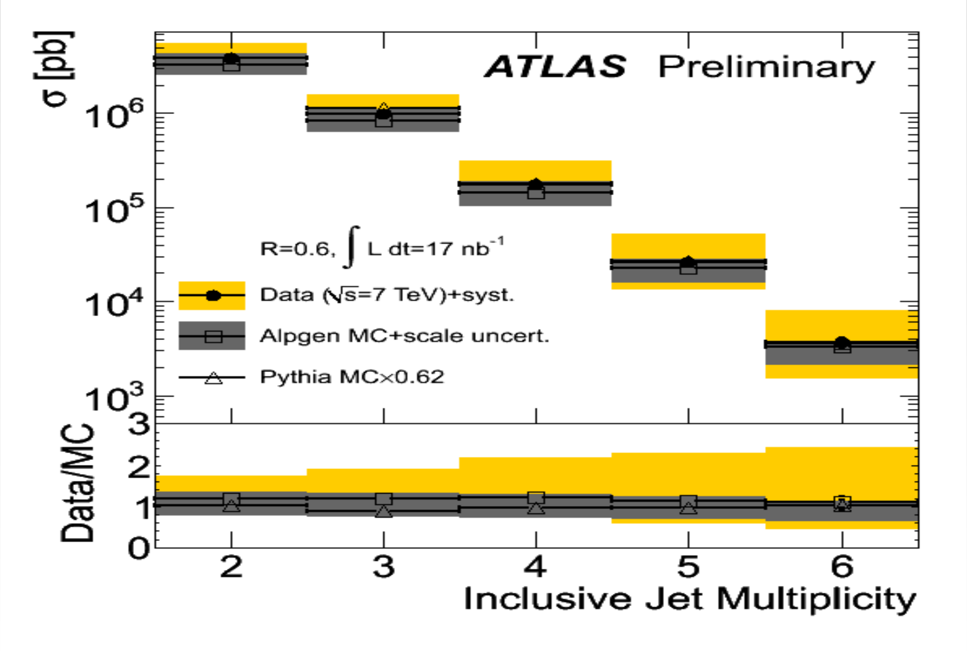
Jets measured from a weighted sum of the energy depositions in various layers of calorimeter, scaled by factors derived from MC and cross-checked with in-situ techniques (track-jets, photon or jet balance)

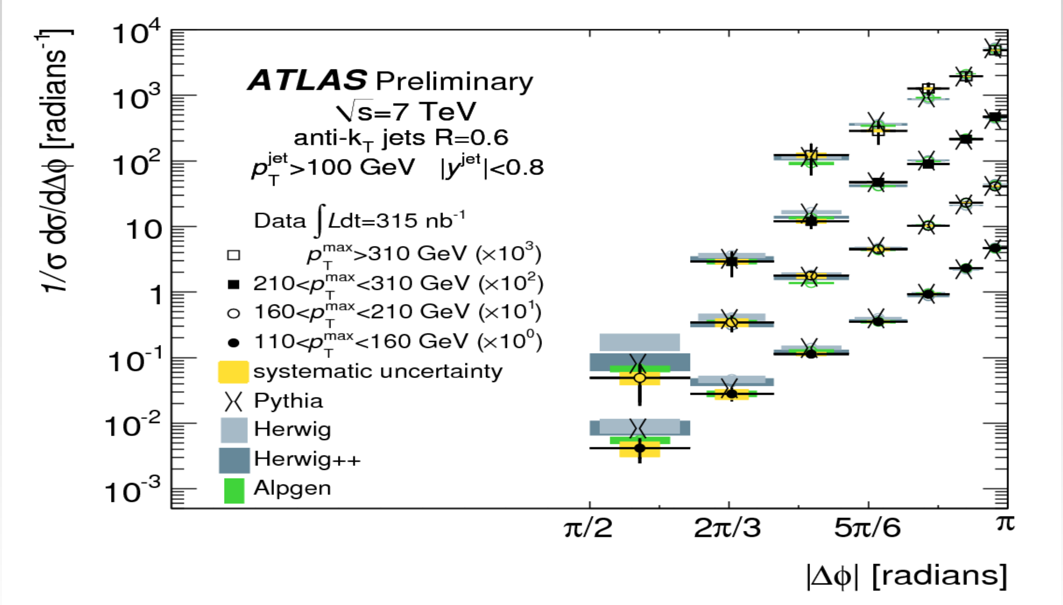
Jet and dijet cross-sections

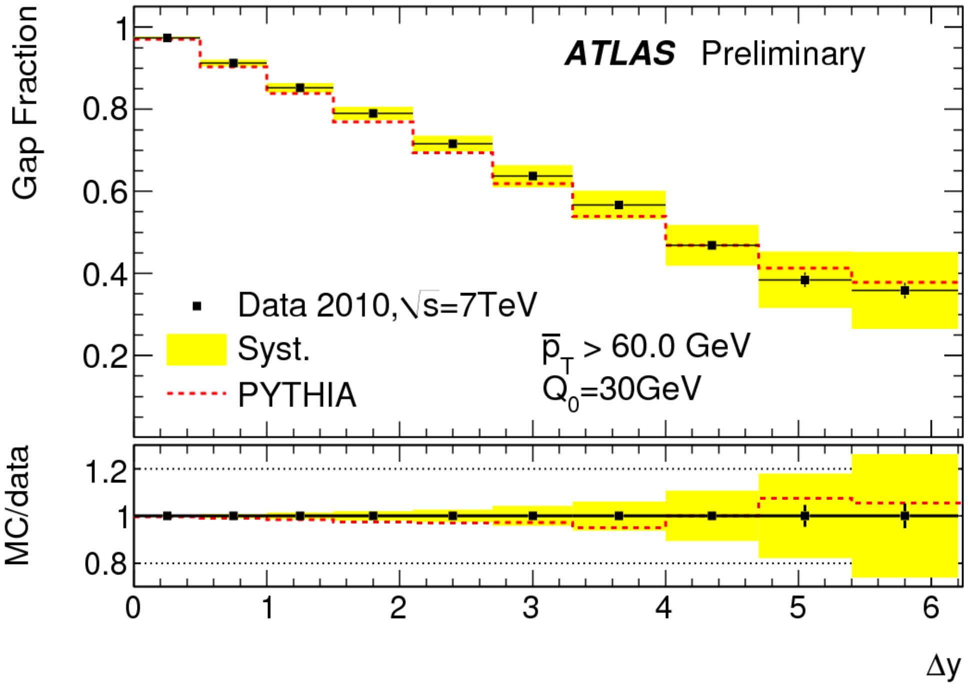




Multijet, de-correlation, gaps





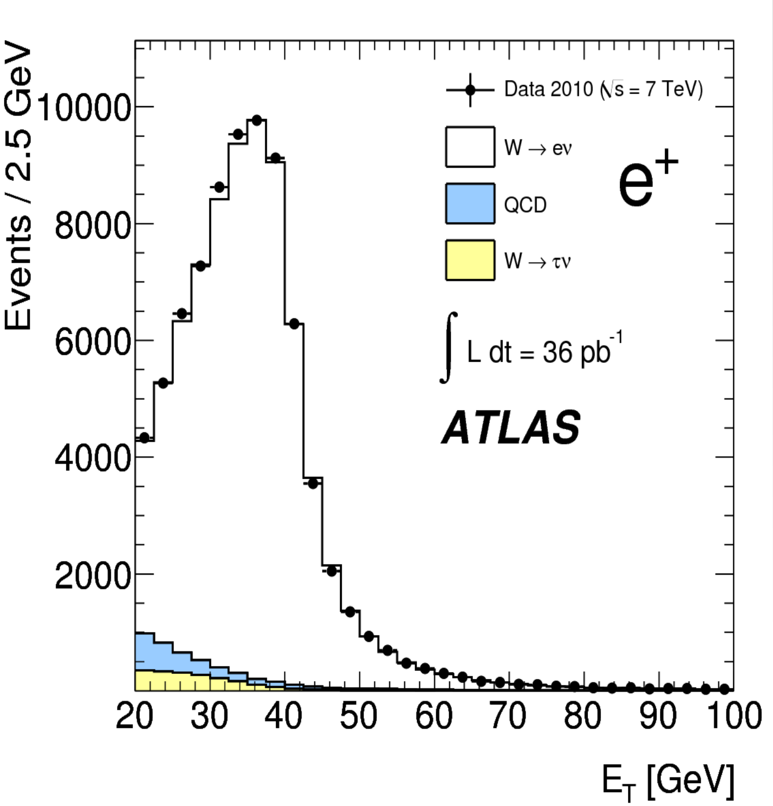


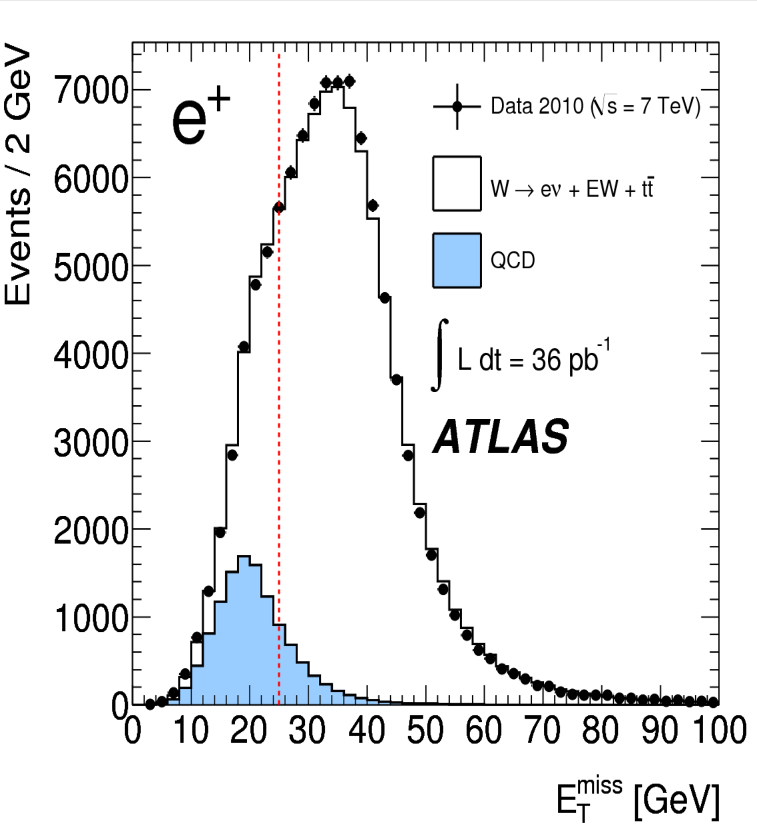
Several QCD tests performed on jets, looking at multiplicity, angular distribution, radiation between dijets

Vector boson production

- Next important SM benchmark are W and Z productin, always accompanied by jets at the LHC.
- Relevant for Pdf determination, QCD studies
- W production about 10 times larger than Z, but analysis more difficult: no way to perform full reconstruction, so only transverse mass can be reconstructed
- Different BG from electron and muon channel:
    - Neutral pions faking electrons
    - Punch-through hadrons in muon chambers
- W forward-backward charge asymmetry very useful for Pdf's (how to define it in a pp machine??)

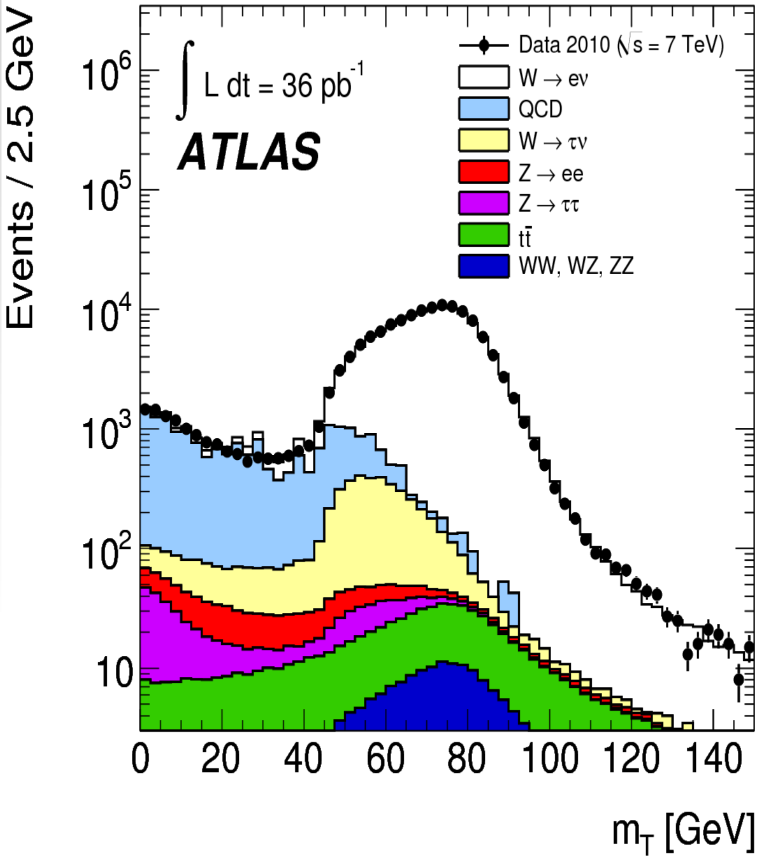
Ingradients of the analysis

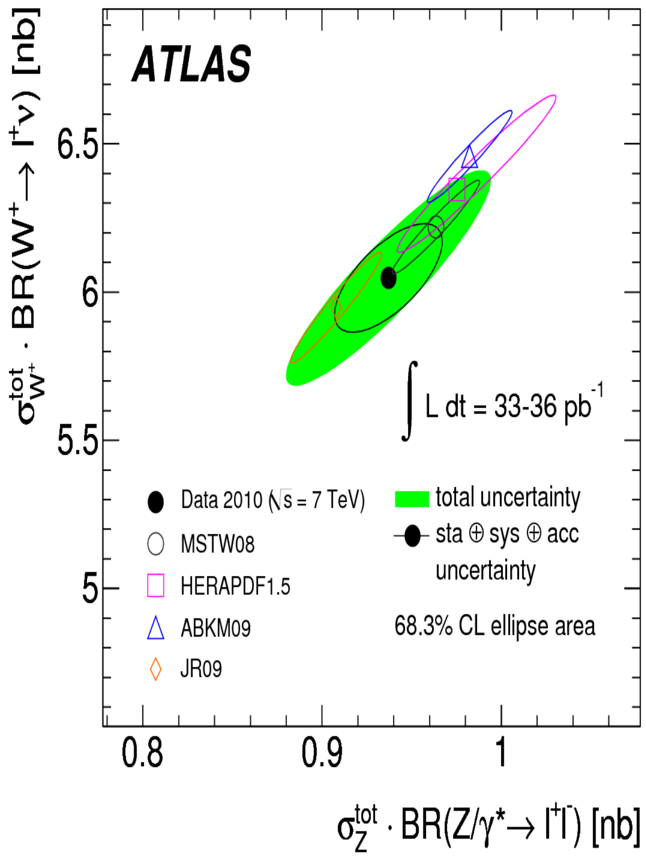


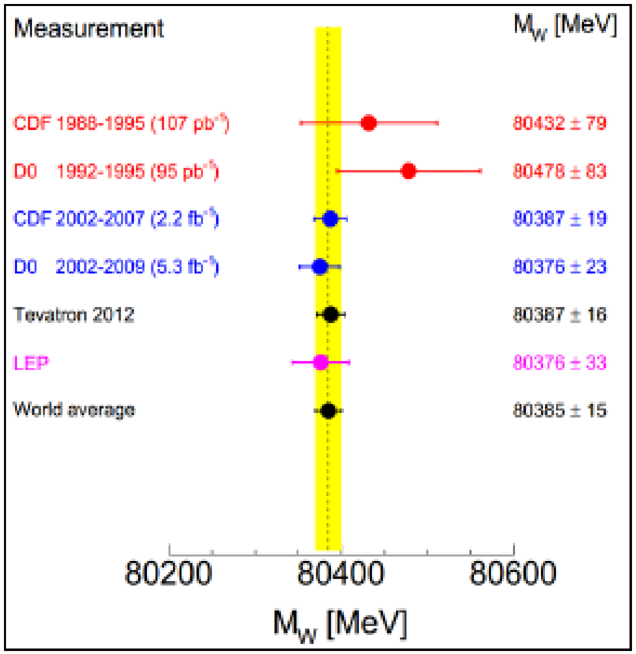


- Electron Pt MET
- for W->enu events
- Signal purity quite low for individual variables

W->e nu transverse mass

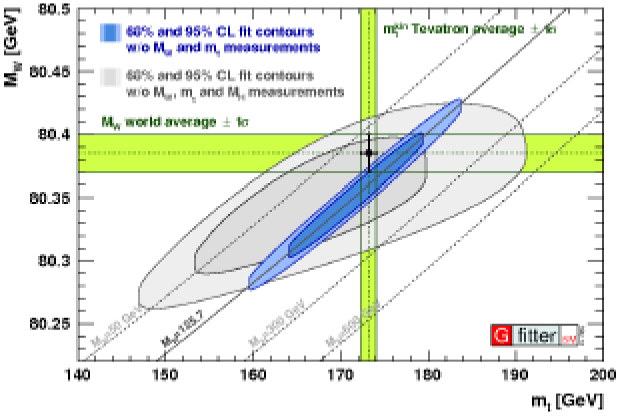






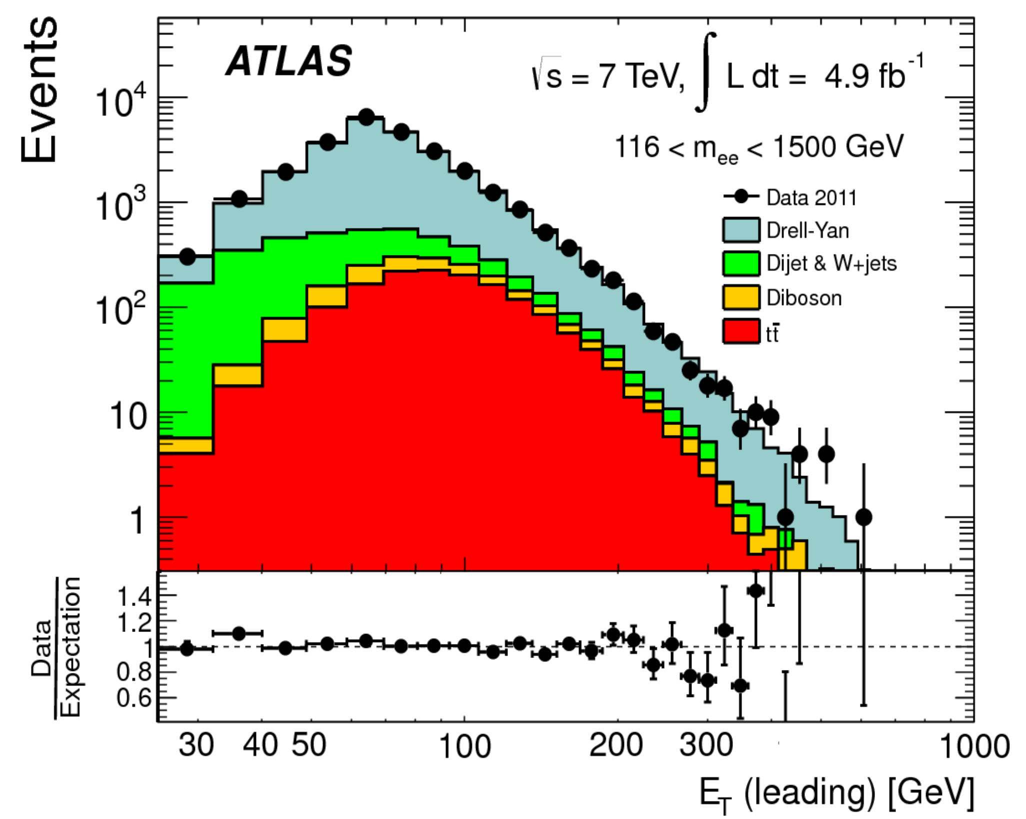
arxiv:1307.7627

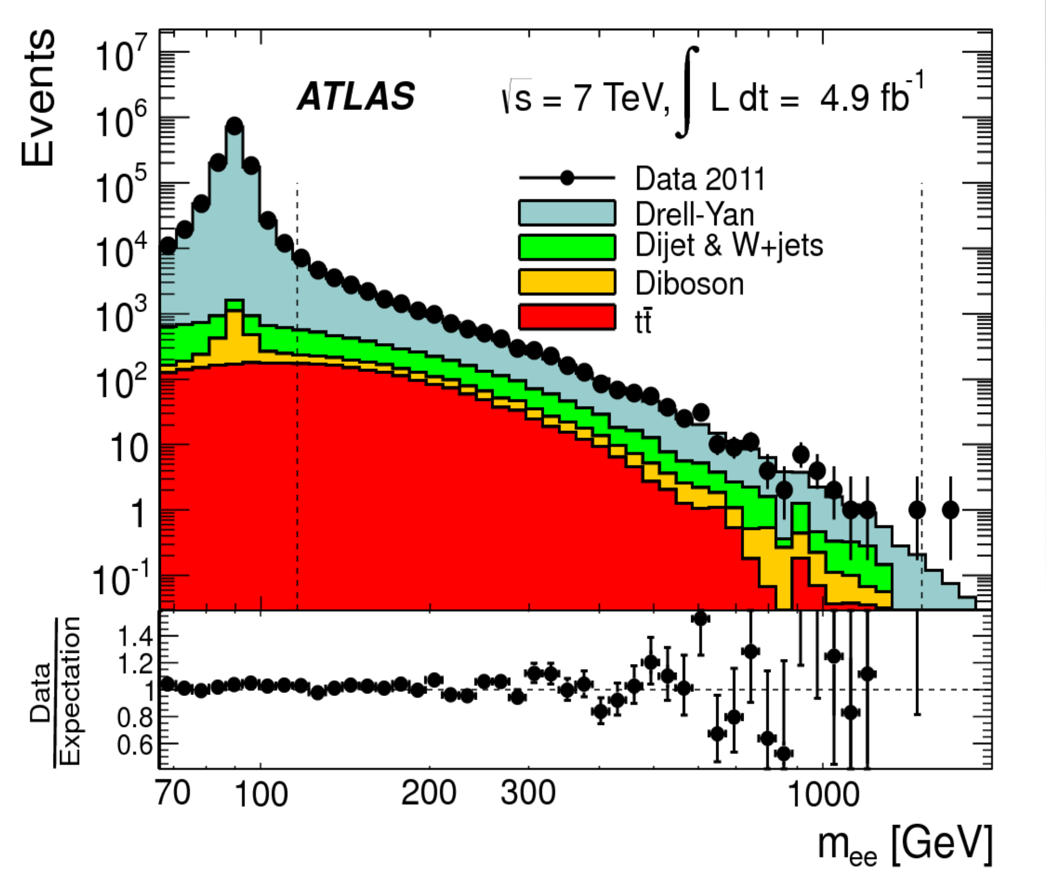
arxiv:1209.2716



- Despite the transverse mass distribution being very broad, Tevatron experiments provide now a measurement of the W mass more precise than that of LEP, where the full mass could be reconstructed

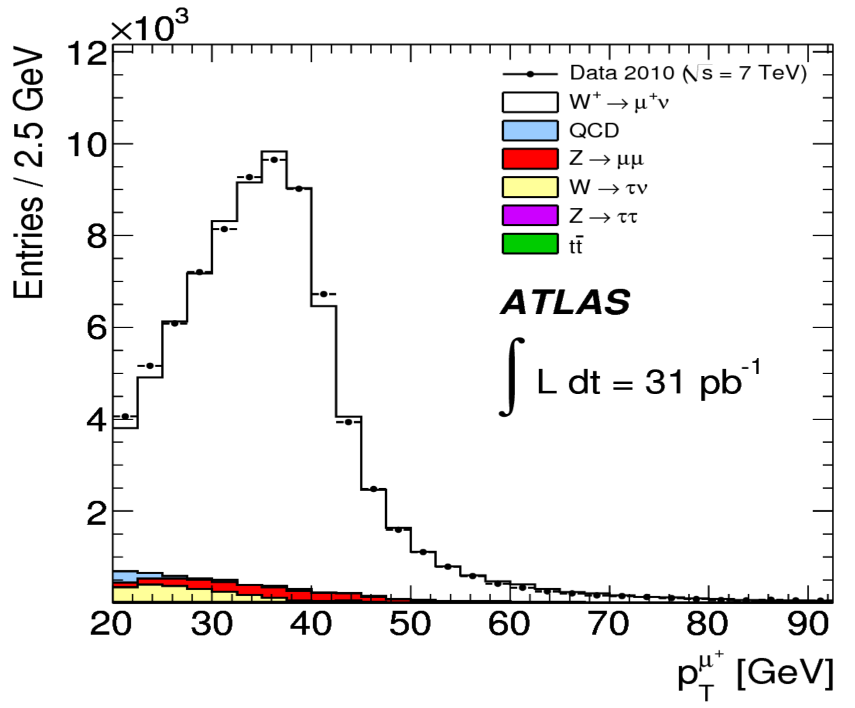
Drell-Yan analysis

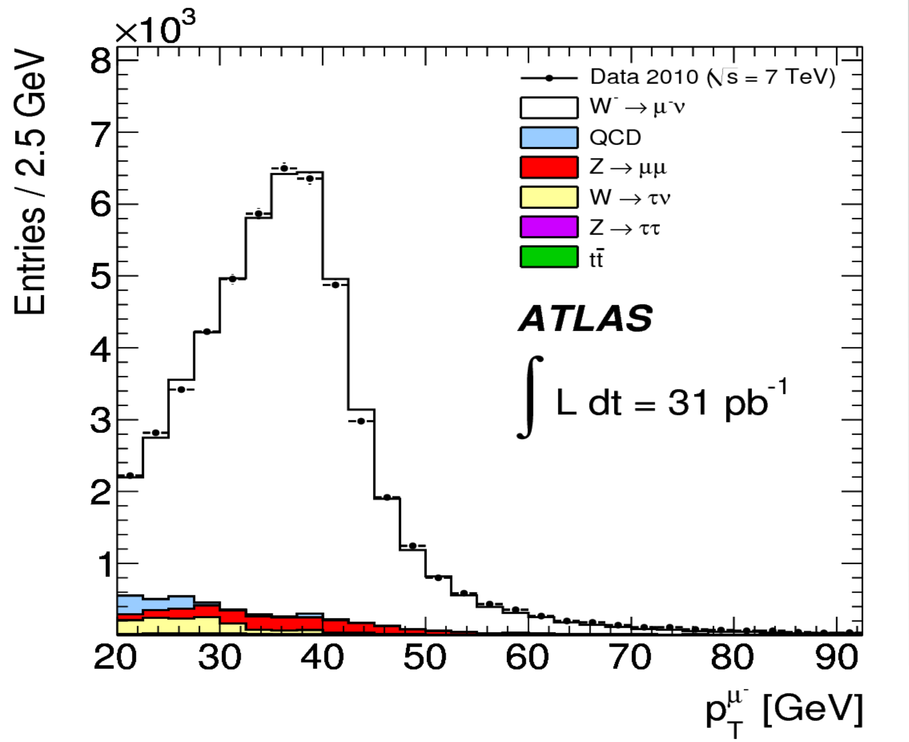


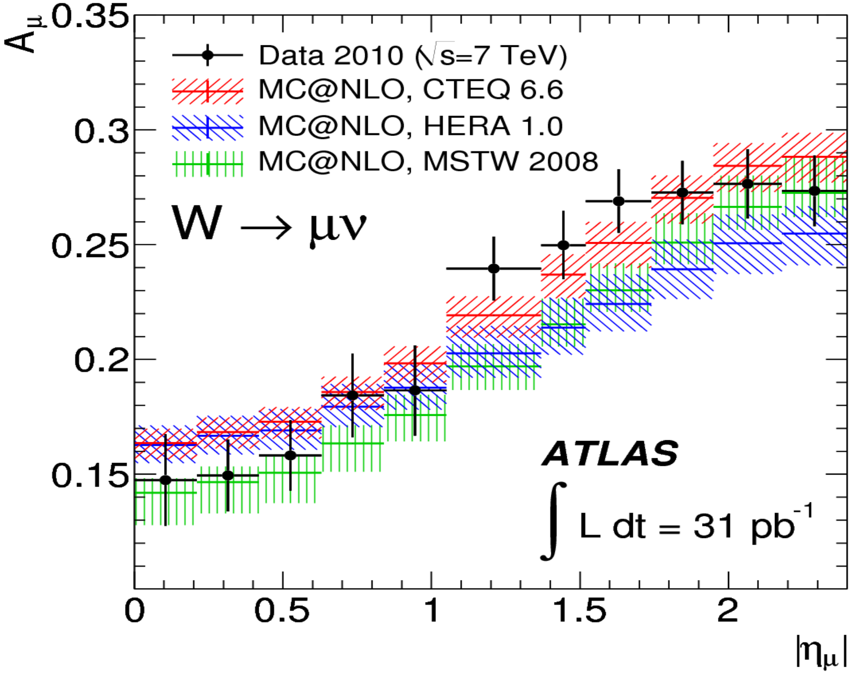


2-lepton requirement makes Z channel much cleaner, but statistics is poorer than W-hard to beat LEP's 4 million Z collected per experiment (and lineshape fit) in clean environment. Fundamental tool for calibration

W charge asymmetry







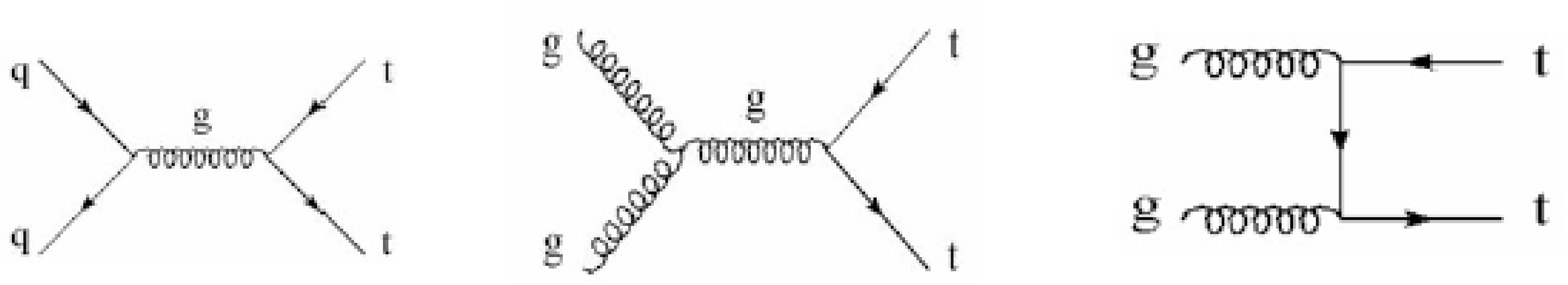
The idea: from Pdf's, u-quarks have higher average x, so W+ tend to be produced more forward. Even in pp, W asymmetry distribution can constraint Pdf's

Top quark @ LHC: production

probe low x in pdfs →
(abundant) gluon fusion dominated

	Tevat	LHC(7)	LHC(14)
gg	~10%	~85%	~90%
qq	~90%	~15%	~10%

top pairs:
strong



Cacciari,Czakon,Mangano,Mitov,
Nason 2011

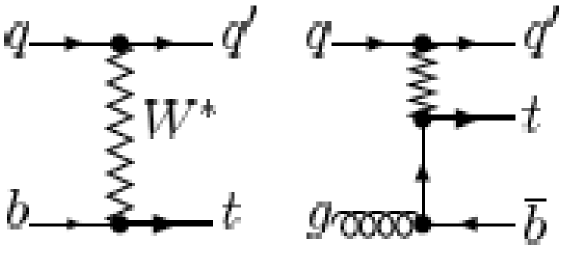
$$\sigma_{7TeV} = 159\,^{+12}_{-13}\,{}^{+4}_{-4}\ \text{pb}$$
$$\sigma_{8TeV} = 227\,^{+18}_{-19}\,{}^{+6}_{-6}\ \text{pb}$$

scales *PDF*

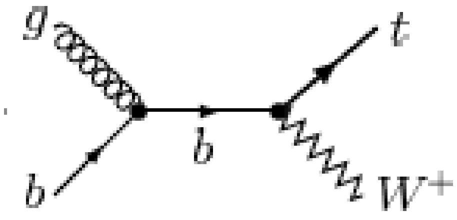
PDF=MSTW2008nnlo68cl
for m_{top}= 173.3

single
top:
electroweak

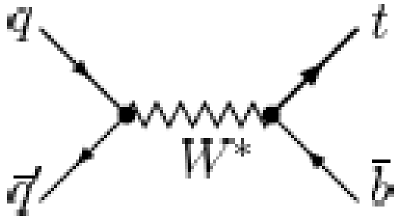
t chan



Wt chan



s chan



Kidonakis
2010,2011

$\sigma_{7TeV} = 64^{+3}_{-3}$ pb
$\sigma_{8TeV} \sim 86$ pb

$\sigma_{7TeV} = 15.7^{+1.3}_{-1.4}$ pb
$\sigma_{8TeV} \sim 22$ pb

$\sigma_{7TeV} = 4.6 \pm 0.3$ pb
$\sigma_{8TeV} \sim 5.6$ pb

Selection/Ingredients for top quark pairs/single-top

ATLAS (CMS is similar)

Event cleaning

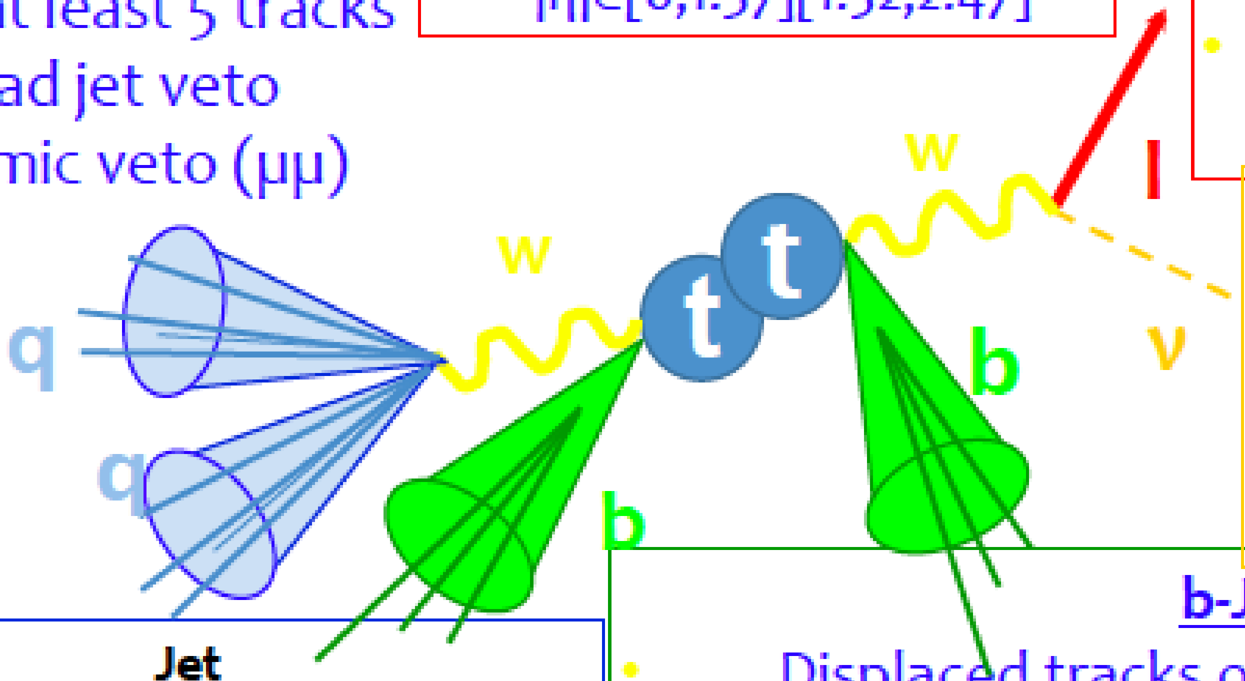
- Good run conditions
- Primary vertex (PV) with at least 5 tracks
- Bad jet veto
- Cosmic veto (μμ)

Electron

- Good isolated calo object
- Matched to track
- E_T>25 GeV
- $|\eta| \in [0;1.37][1.52;2.47]$

Muon

- Segments in tracker and muon detector
- Calo and track isolation
- p_T > 20 GeV $|\eta|$ < 2.5 (2.1 for CMS)



E_T^{miss}

- Vector sum of calo energy deposits
- Corrected for identified objects

Jet

- Topological clusters, Anti-k_T (R=0.4)
- MC Calibration checked w/data
- p_T > 25 (20) GeV (30 for CMS), $|\eta|$ < 2.5
- (large JVF =$\sum_{\text{jet trk in PV}} p_T / \sum_{\text{jet trk}} p_T$ vs pile-up jets, CMS: use particle flow to remove charged hadrons not from prim verted)

b-Jet

- Displaced tracks or secondary lepton
- SV0: reconstruct sec.vertex
- JetProb: track/jet compatibility with prim. vertex
- IP3D+SV1 +/or JetFitter: advanced lkl/NN taggers

Measurement of σ_{tt} - single lepton

$\int L dt =$ **~0.7 fb^{-1}** *(2011)*

ATLAS-CONF-2011-121

- **Extract σ_{tt} ,σ_{bkg} by binned maximum likelihood fit of discriminant** to data **in** 3, 4 and **≥ 5**-jet bins

image by J Andrea (CNRS,strasbourg)

- Likelihood defined as :

σ_{tt}, backgrounds

Detector-related syst.

Background normalization constrained by the fit

$$\mathcal{L}(\vec{\beta},\vec{\delta}) = \boxed{\prod_{k=1}^{120} \mathcal{P}(\mu_k, n_k)} \times \boxed{\prod_{j} \mathcal{G}(\beta_j, \Delta_j)} \times \boxed{\prod_{i} \mathcal{G}(\delta_i, 1)}$$

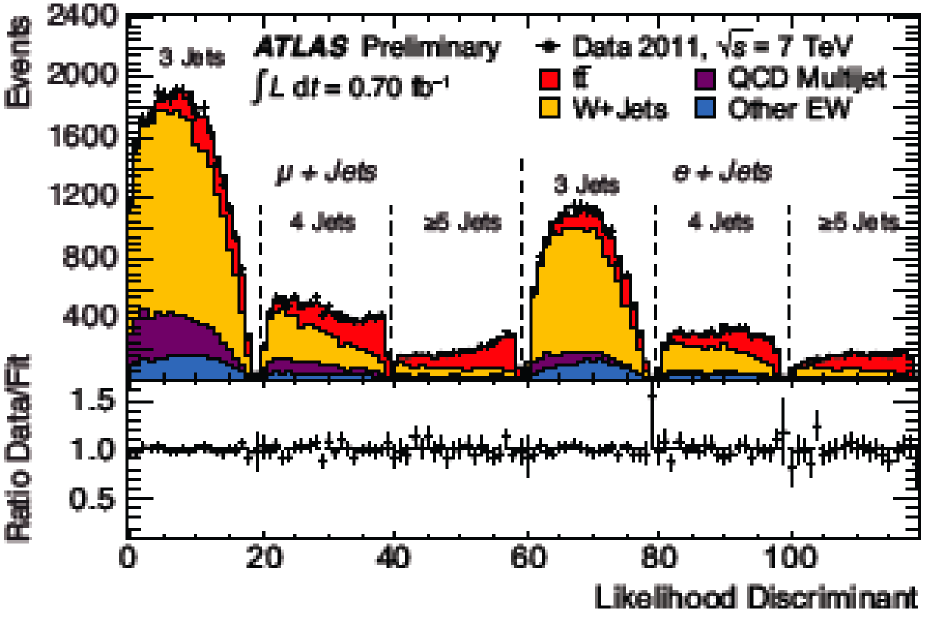
Interlude on Tools

parametrized lkl= Profile lkl

Poisson proba. density to observe n_k when μ_k is expected

Free parameters constrained by Gaussian distributions

Introduce sytematics as nuisance parameters



- **most syst uncertainties part of lkl fit** as Gaussian nuisance parameters→reduction in JES,ISR/FSR (20% to 70% of initial value)
- still syst-dominated: generator ~3% lepton scale~2%
- δσ/σ=6.6% (stat~0.5%, sys~5%)

$$\sigma_{t\bar{t}} = 179.0 \pm 3.9\,(\mathrm{stat}) \pm 9.0\,(\mathrm{syst}) \pm 6.6\,(\mathrm{lumi})\ \mathrm{pb}$$

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Measurement of σ_{tt} - LHC Combination @ s = 7 TeV

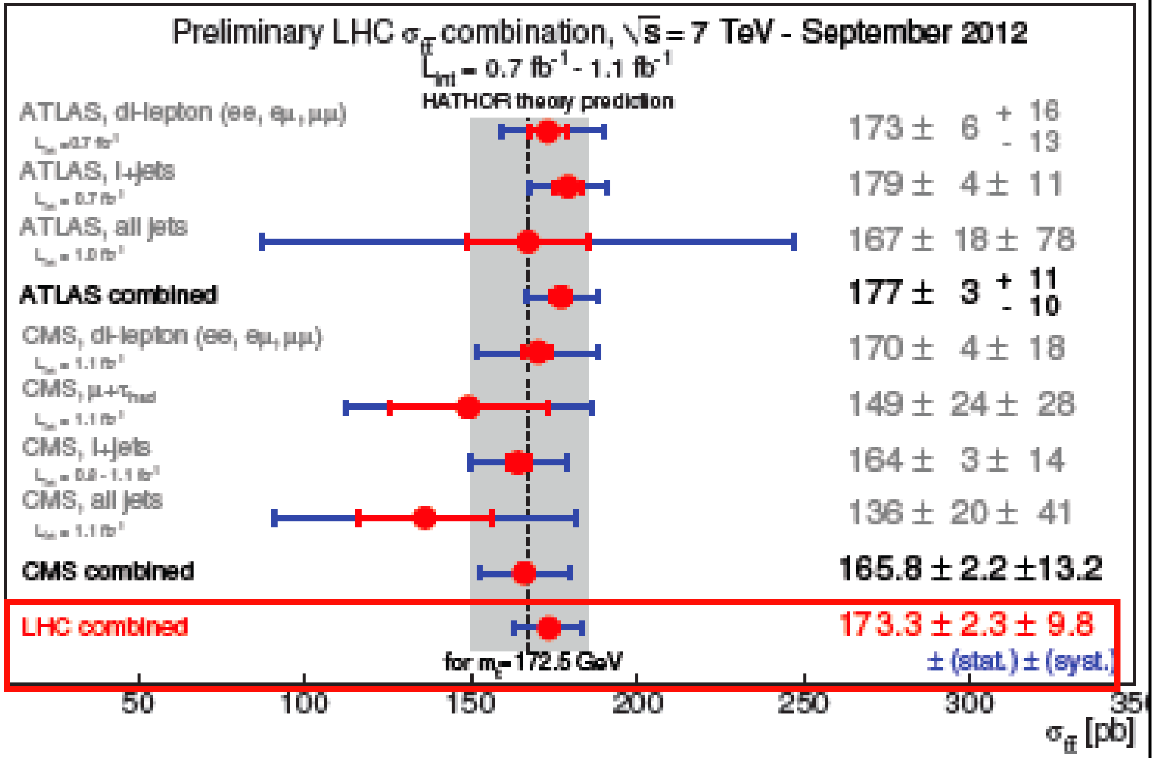
	ATLAS	CMS	Correlation	LHC combination
Cross-section	177.0	165.8		173.3
Uncertainty				
Statistical	3.2	2.2	0	2.3
Jet Enegy Scale	2.7	3.5	0	2.1
Detector model	5.3	8.8	0	4.6
Signal model				
Monte Carlo	4.2	1.1	1	3.1
Parton shower	1.3	2.2	1	1.6
Radiation	0.8	4.1	1	1.9
PDF	1.9	4.1	1	2.6
Background from data	1.5	3.4	0	1.6
Background from MC	1.6	1.6	1	1.6
Method	2.4	n/e	0	1.6
W leptonic branching ratio	1.0	1.0	1	1.0
Luminosity				
Bunch current	5.3	5.1	1	5.3
Luminosity measurement	4.3	5.9	0	3.4
Total systematic	10.8	14.2		9.8
Total	11.3	14.4		10.1

- Combine with best linear unbiased estimator
- Total correlation~30%

ATLAS-CONF-2012-134 & CMS-PAS-TOP-12-003

- Improvement by 7% (11%) w.r,t most precise l+jets channel
- **Final δσ/σ~5.8% (10 pb)**

$$\sigma_{t\bar{t}} = 173.3 \pm 2.3(\text{stat.}) \pm 9.8(\text{syst.})\ \text{pb}$$



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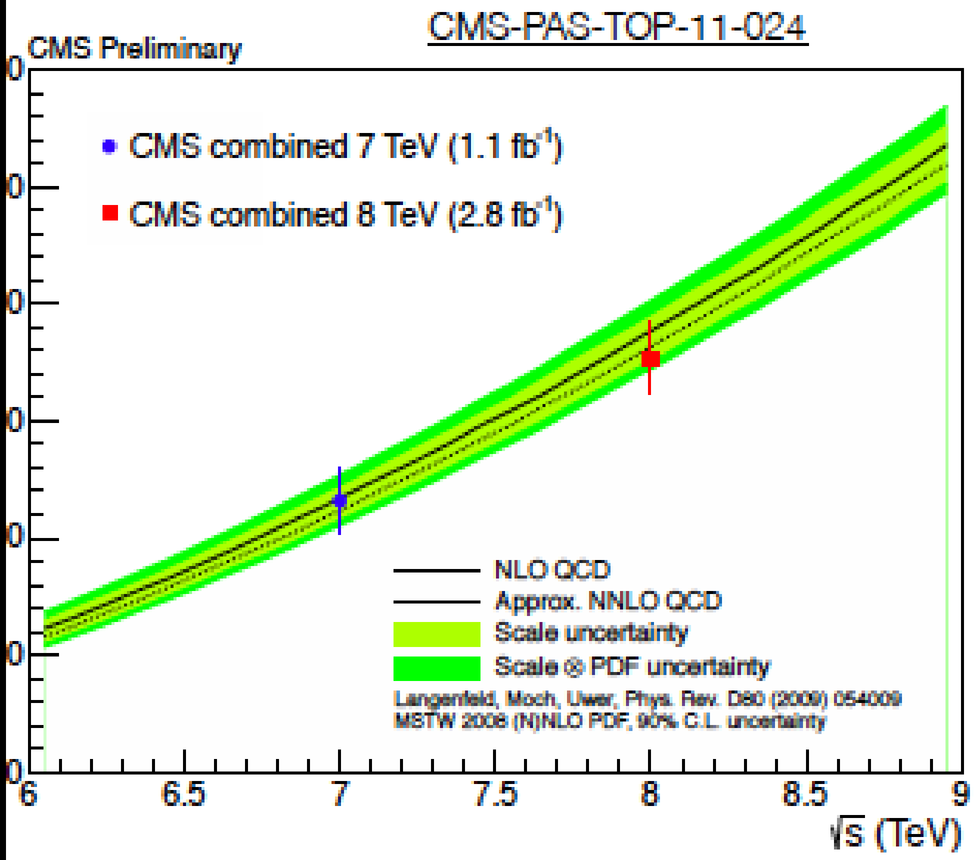
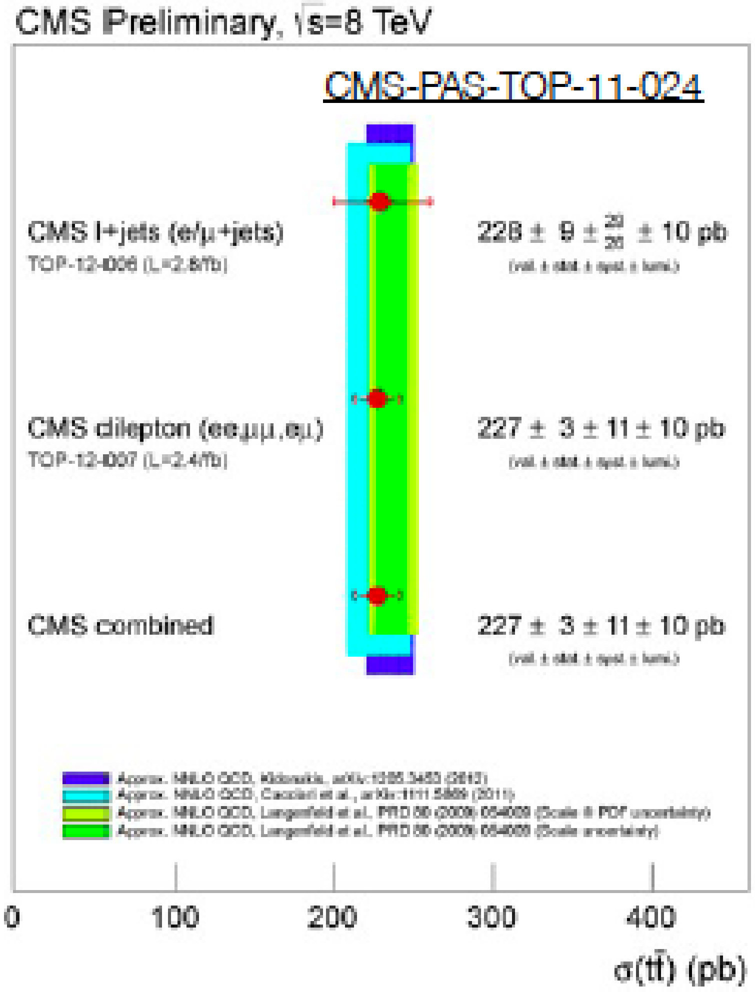
Measurement of σ_{tt} - CMS Combination @ s = 8 TeV

- Combination of 8 TeV measurements (CMS)with best linear estimator, dominated by dilepton measurement

$$\boxed{\sigma_{t\bar{t}} = 227 \pm 3\,(\text{stat.}) \pm 11\,(\text{syst.}) \pm 10\,(\text{lumi})\text{ pb}}$$



δσ/σ~6.6%



- Ratio of 8 TeV to 7 TeV cross section is 1.41 0.10
  - partial cancellation of syst effects

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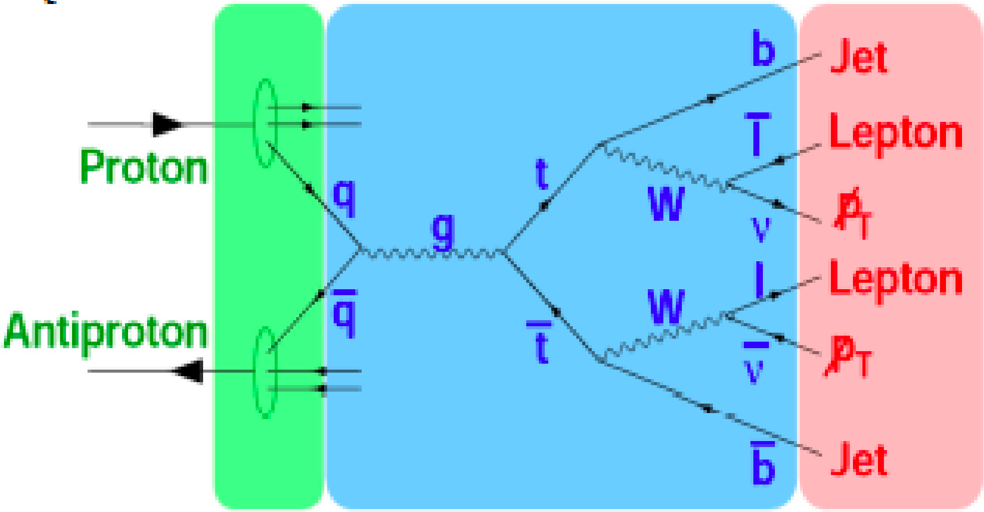
Top Quark Mass: Matrix Element Method

- Use full event kinematics → most precise method
- For each event calculate probability to belong to certain top mass

$P_{sig}(x;m_t) \propto \int$ PDF x Matrix element x Transfer function

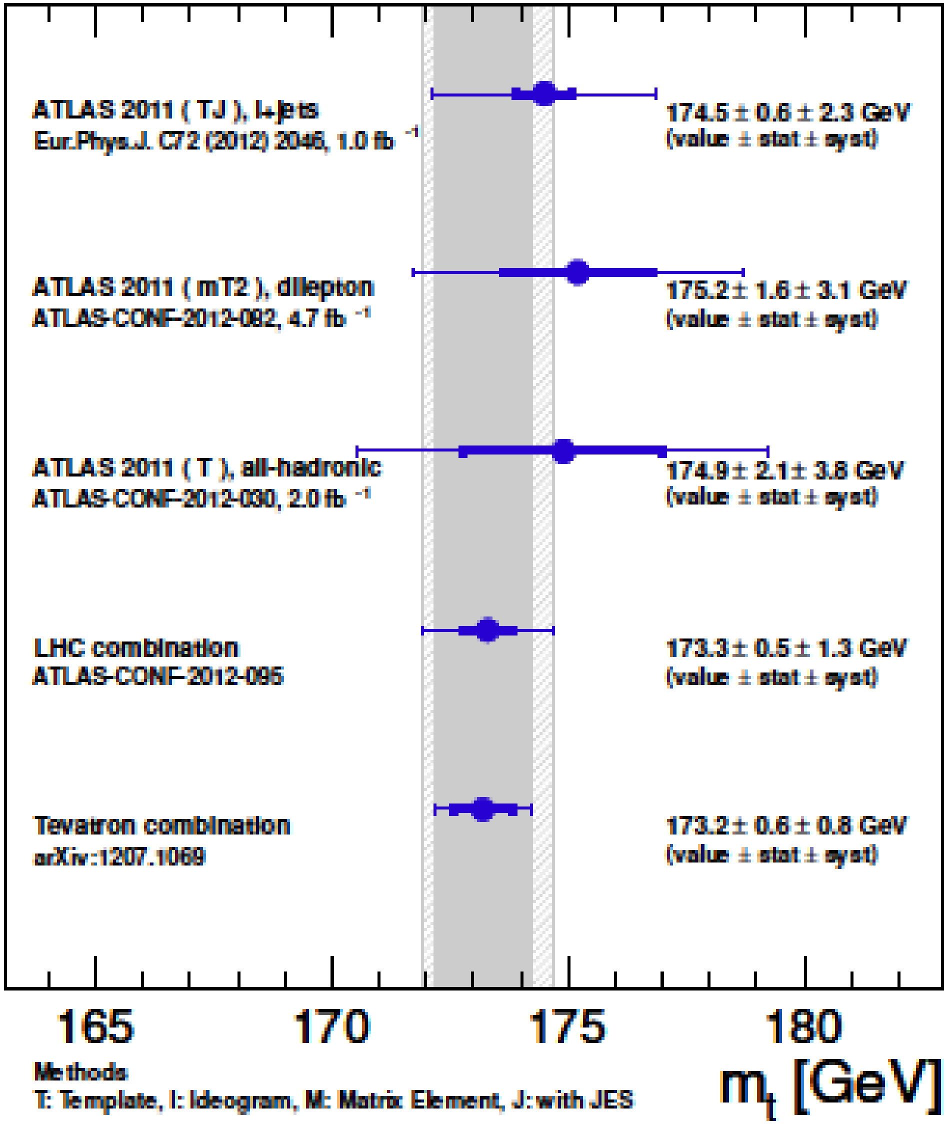


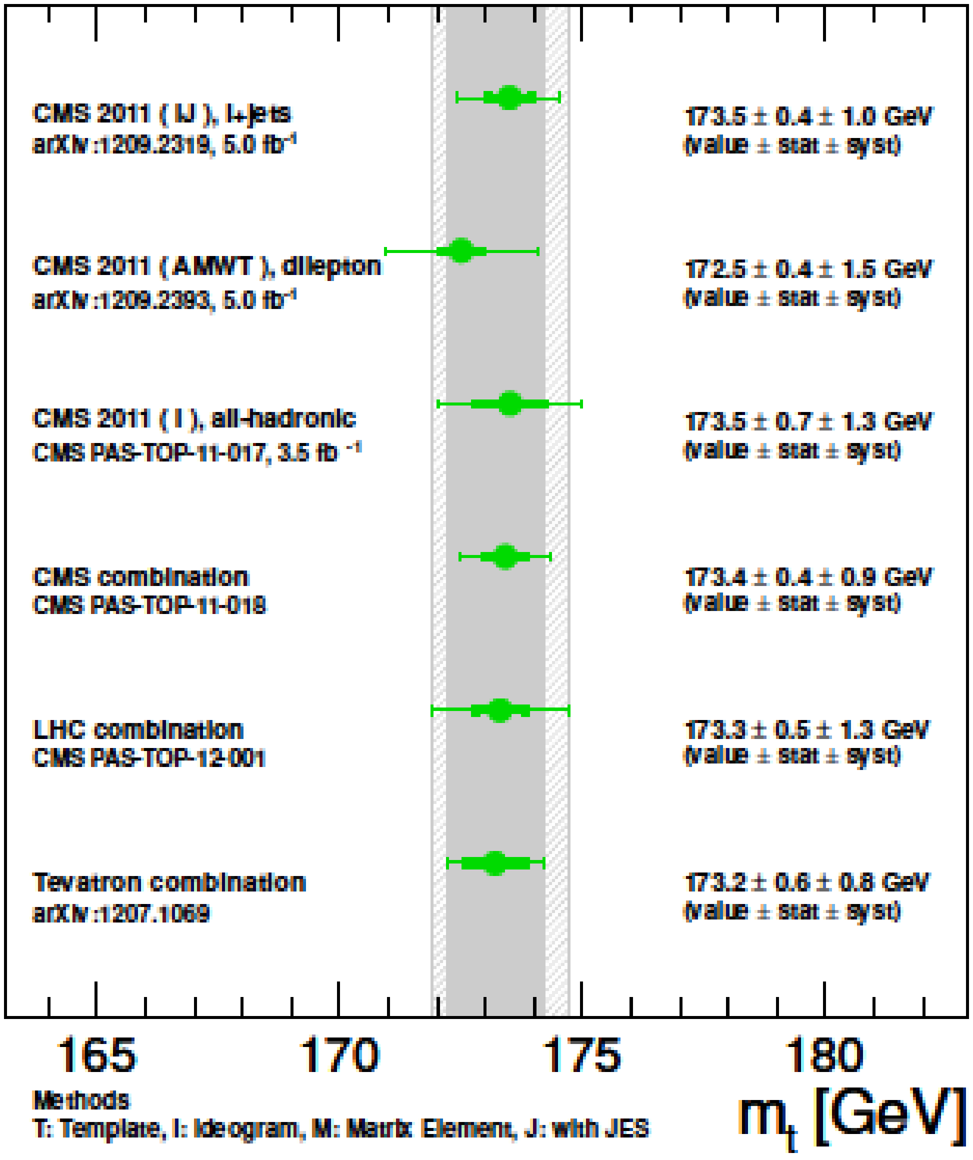
Y. Peters PIC2011

- Perform likelihood fit of event probabilities
- Probability depends on top mass (& JES for in-situ fit)
- Used in l+jets & dilepton final states

Overall Status of m_t - LHC+Tevatron

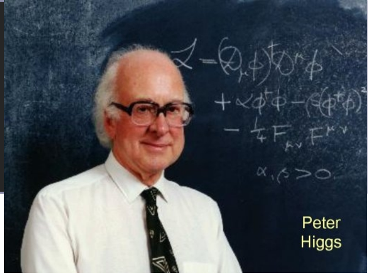
(M Seidel, TOP2012)



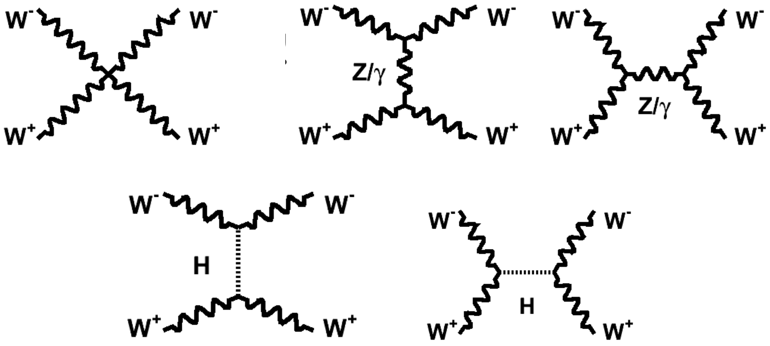


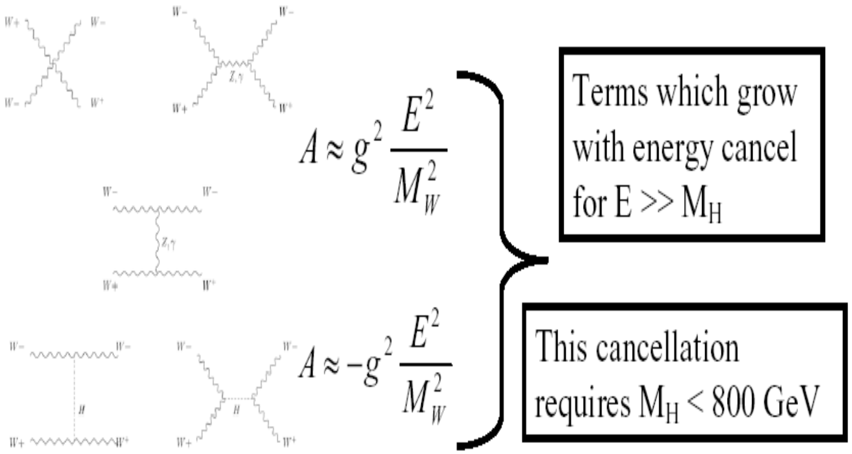
The Higgs Boson

Peter Higgs



- EWSB caused by scalar Higgs field
- vacuum expectation value of the Higgs field <☙> =246 GeV/c2
  - gives mass to the W and Z gauge bosons,
    - MW ⬥ gW<⇆>
  - fermions gain a mass by Yukawa interactions with the Higgs field,
    - mf ⬥ gf<⇆>
  - Higgs boson couplings are proportional to mass
- Higgs boson prevents unitarity violation of WW cross section
  - ☙(pp□ WW) > ☙(pp □ anything)
    - => illegal!





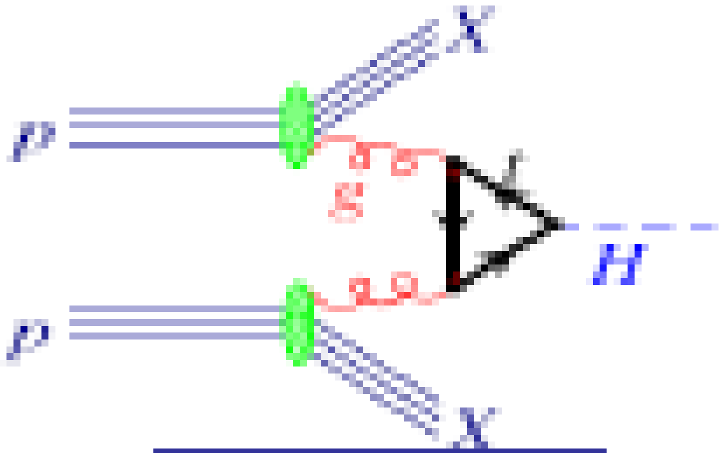
$$A \approx g^2 \frac{E^2}{M_W^2}$$

$$A \approx -g^2 \frac{E^2}{M_W^2}$$

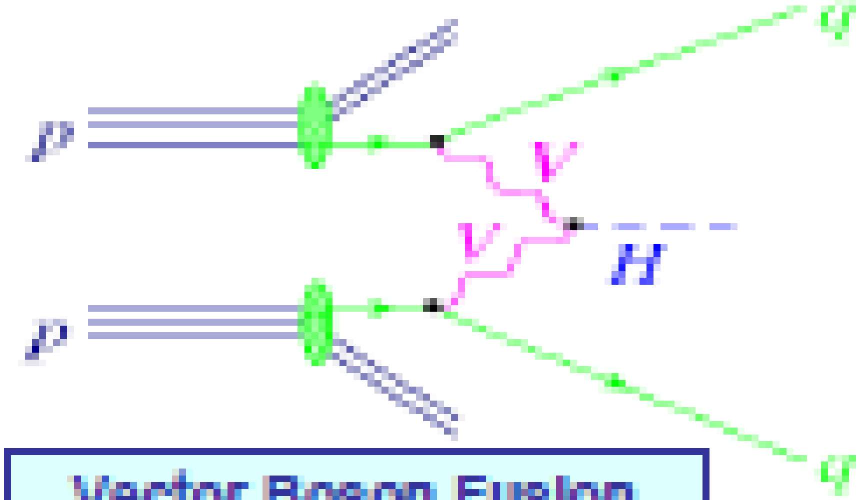
Terms which grow with energy cancel for E >> M_H

This cancellation requires M_H < 800 GeV

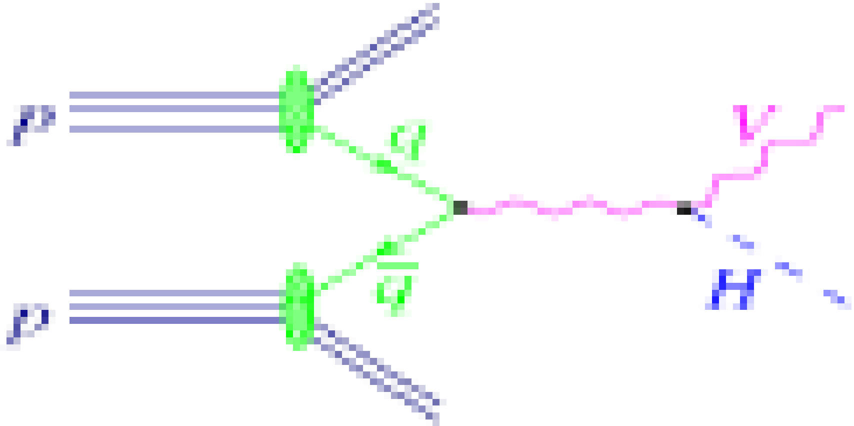
Standard model Higgs production



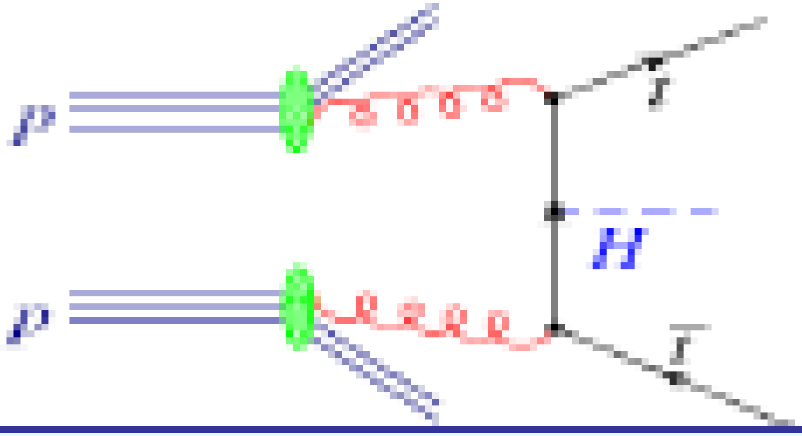
Gluon Fusion



Vector Boson Fusion

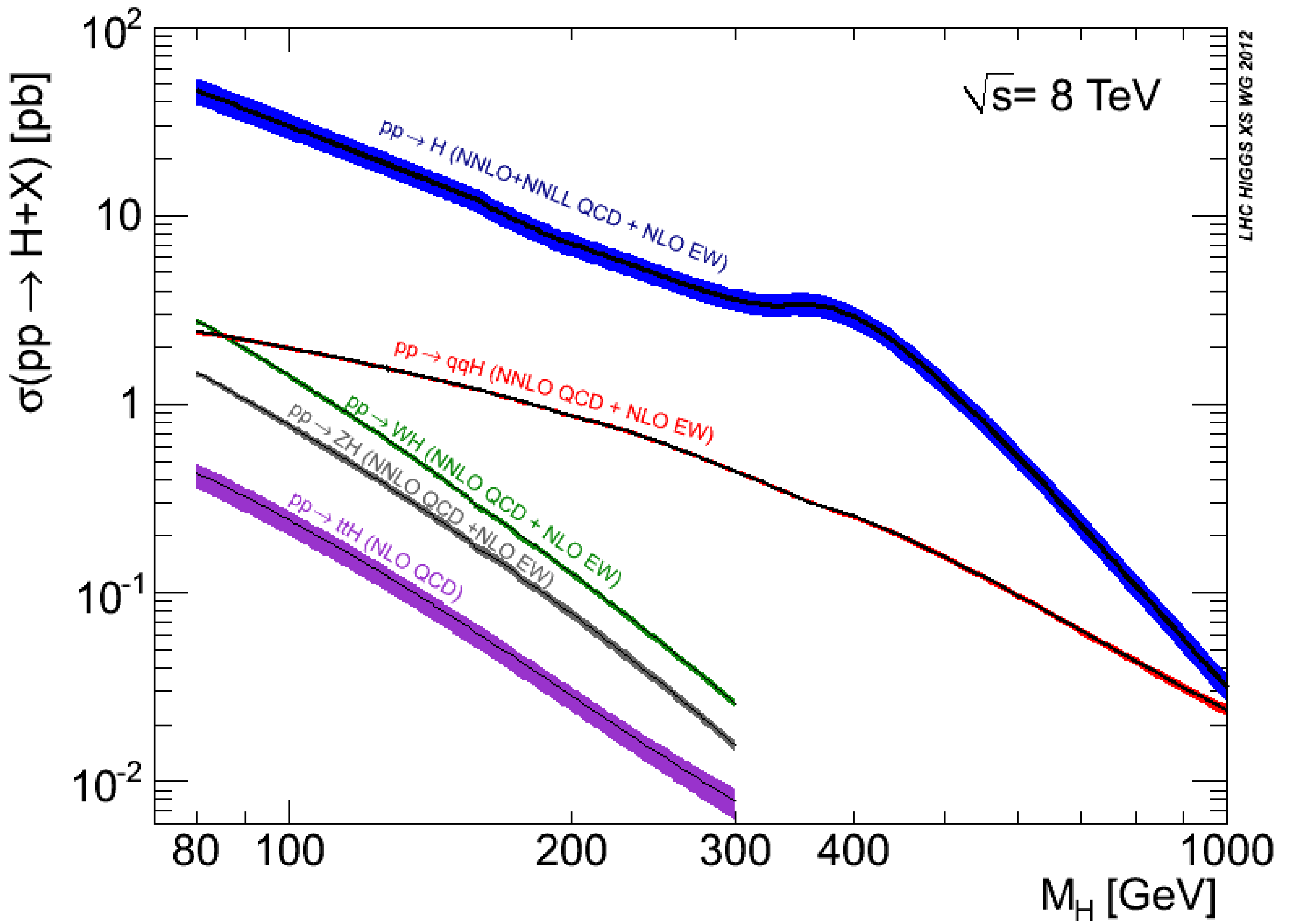


Higgs-strahlung



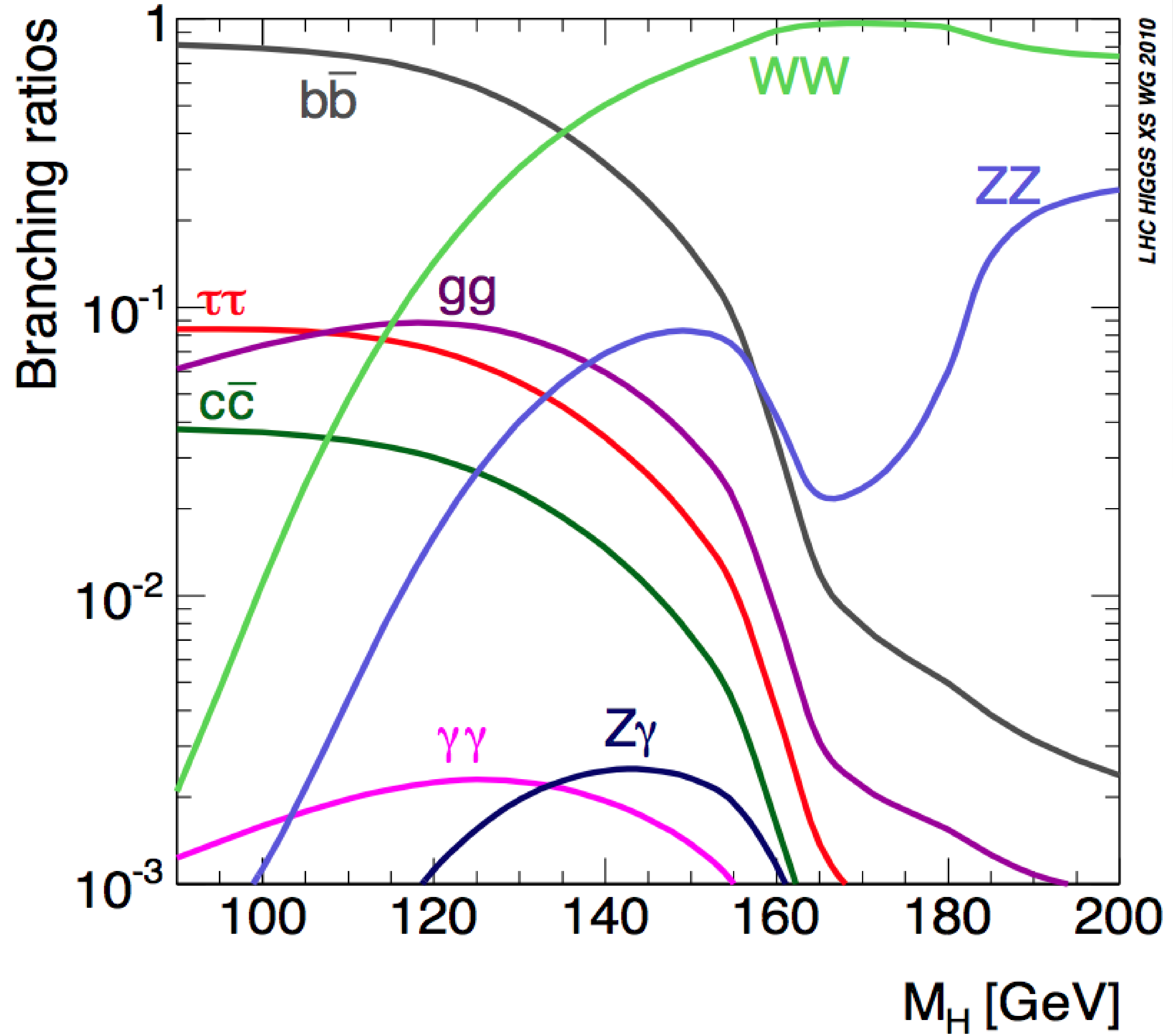
ttbar H ("associated" production)

Higgs cross section: NNLO+NNLL

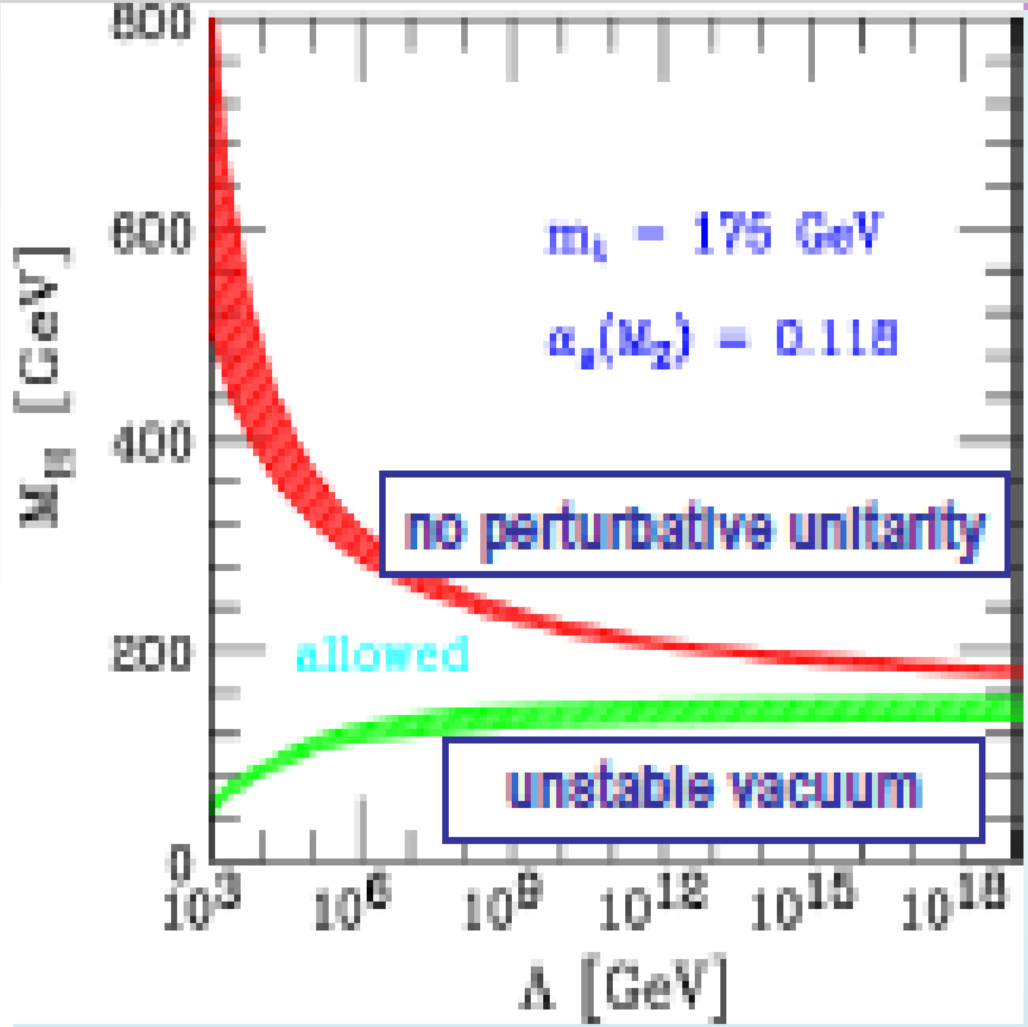


Higgs width ~ (m_H)

Main decay modes



Theory constraints to mass



Upper bound

(triviality) :

$$\Lambda \le M_H \exp\left(\frac{4\pi^2 v^2}{3M_H^2}\right)$$

Lower bound

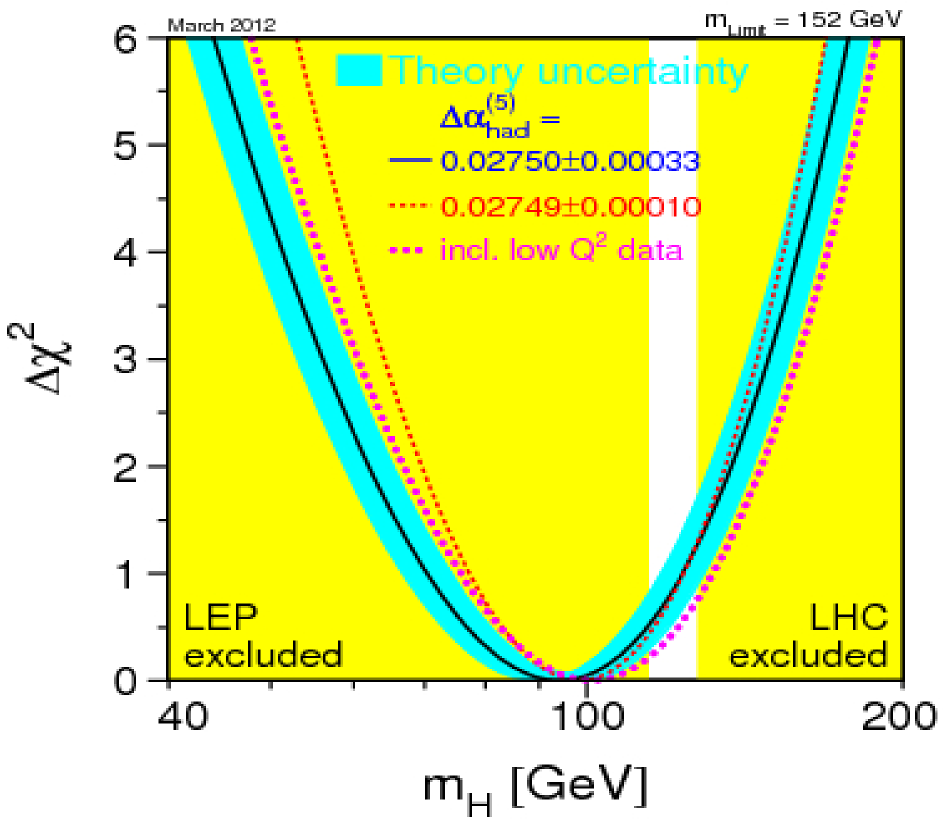
(vacuum stability) :

$$M_H^2 > \frac{3G_F\sqrt{2}}{8\pi^2} F \log\left(\Lambda^2 / v^2\right)$$

(Λ = cut-off scale at which new physics becomes important)

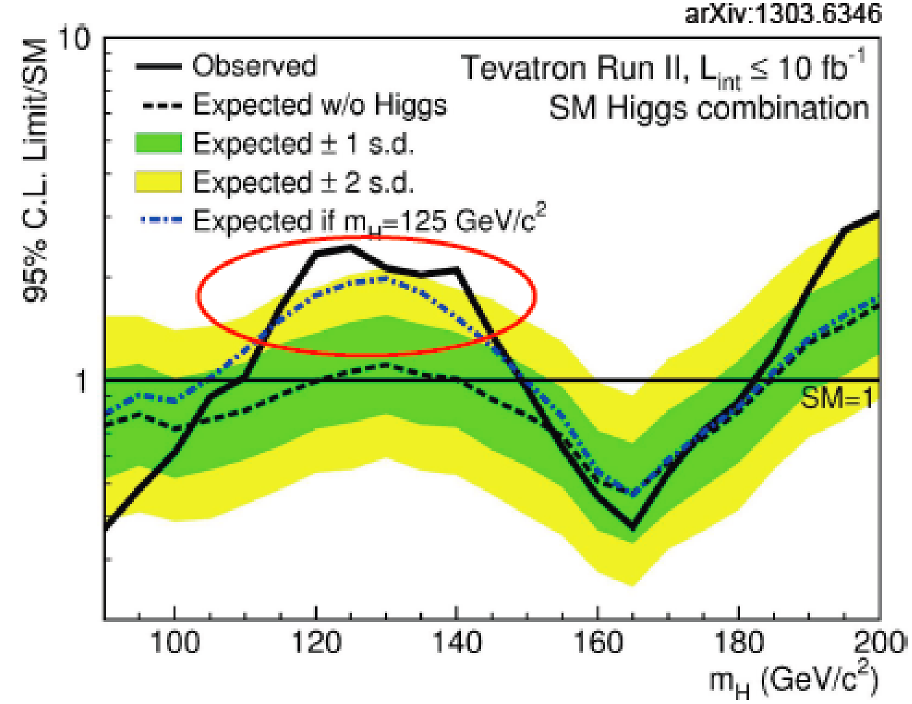
A light or heavy higgs requires early SM breakdown, and new physics to be discovered soon; worst case scenario mH ~ 180 Gev

Experimental constraints to Higgs mass



Best-fit value already escluded by LEP;

- Indirect from EW fits, direct from LEP and Tevatron searches



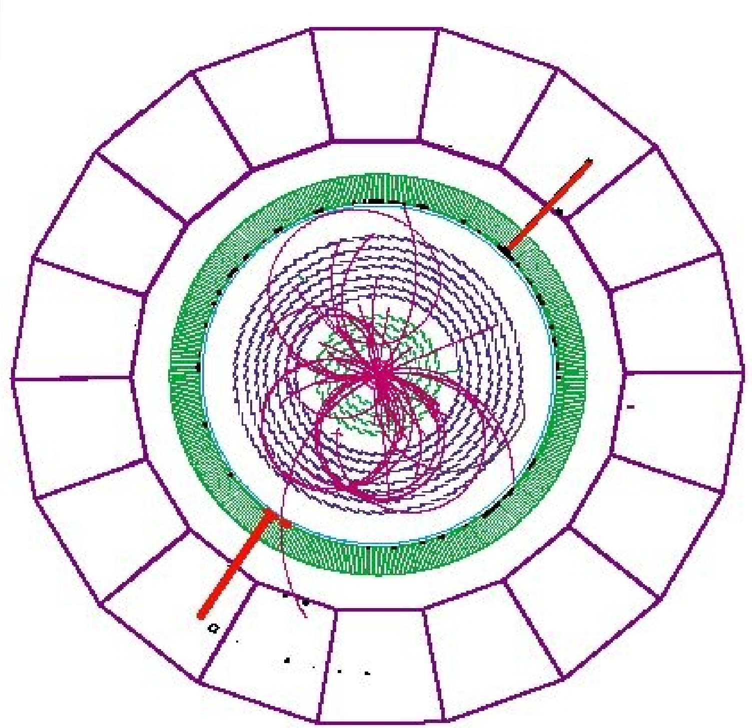
How to look for the SM Higgs

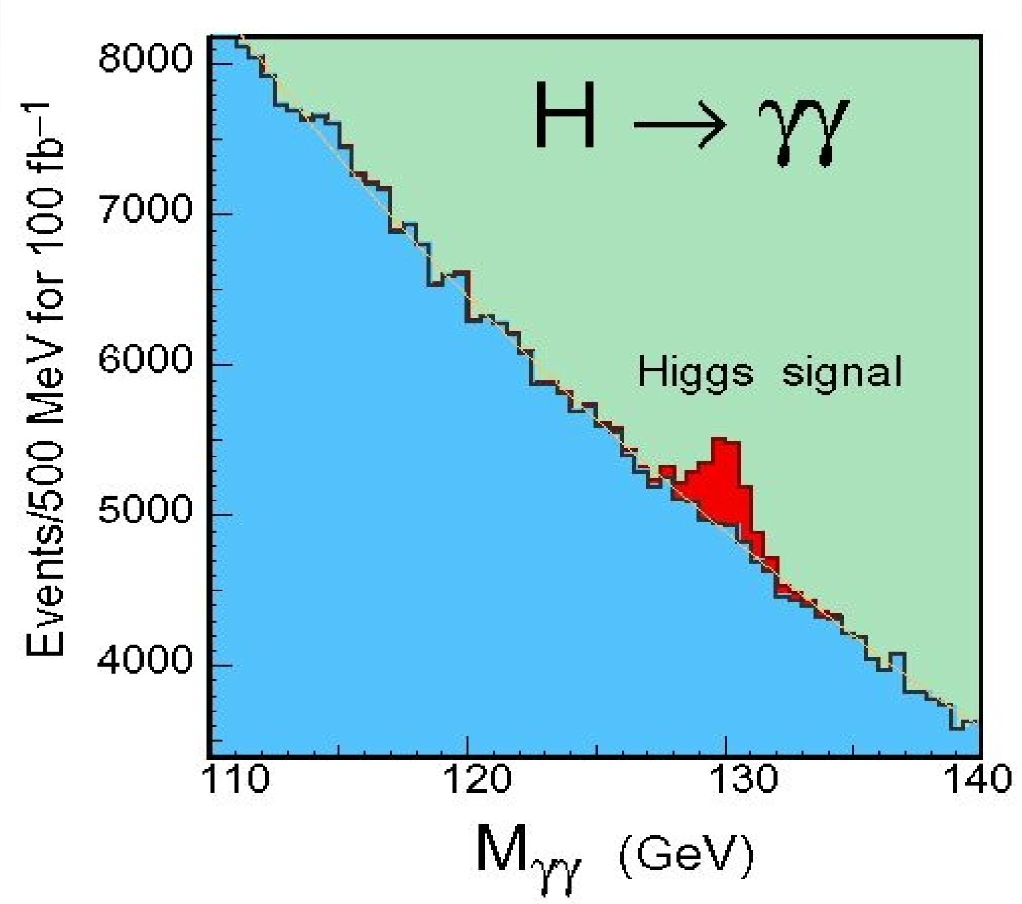
Only unknown is mass, search was done in several channels, depending on possible values Higgs mass:

- Light Higgs: $114 < mH < 130$
    - $H \rightarrow \gamma\gamma$, $qqH \rightarrow qq\tau\tau$
    - $qqH \rightarrow qq\, WW^*$, $ttH \rightarrow ttbb$
- As soon as two (even virtual) vector bosons can be produced
    - $H \rightarrow WW^{(*)}$
    - $H \rightarrow ZZ^{(*)}$, ZH->llbb
- At high masses, the width becomes very large, so we would see a shoulder rather than a resonance

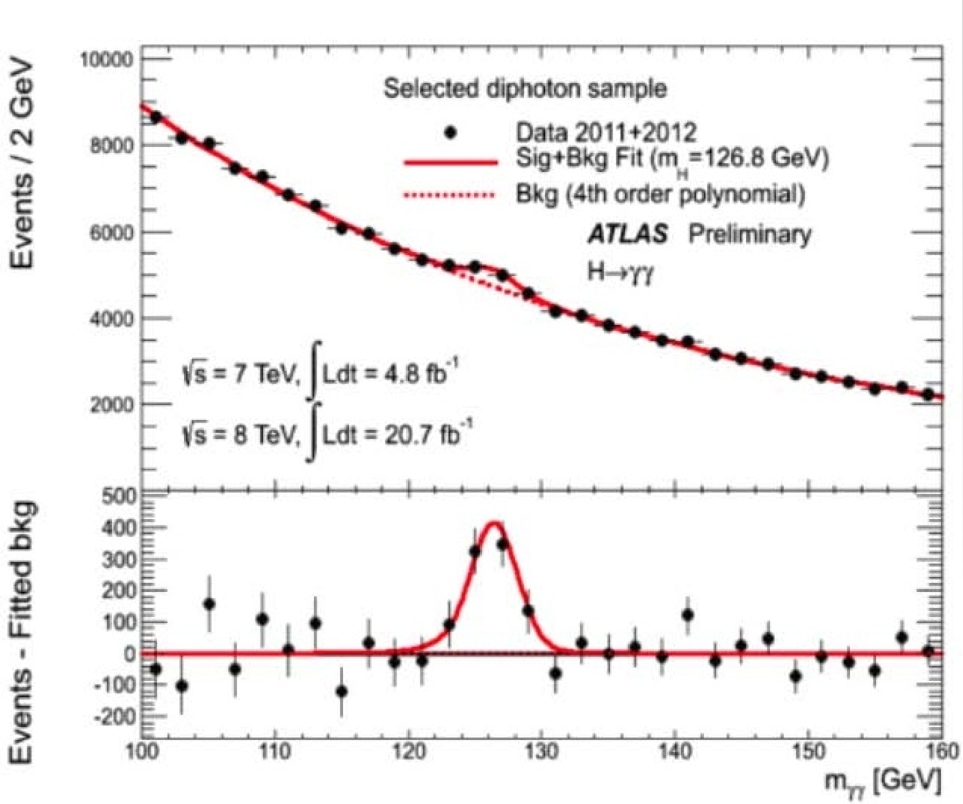
H->$\gamma\gamma$

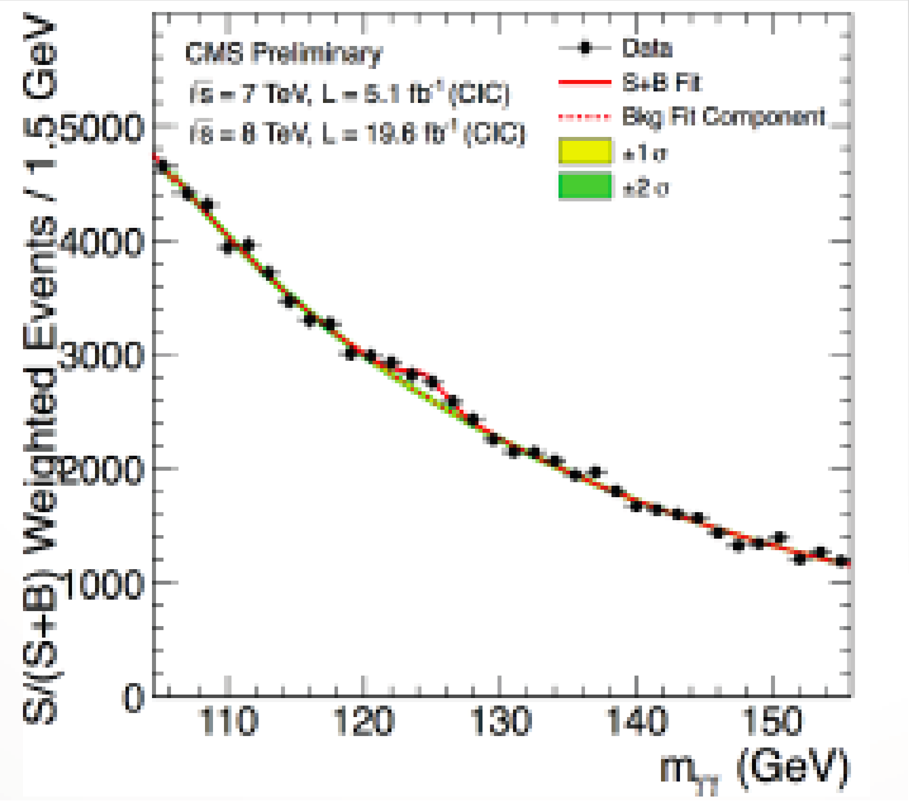
- Small signal (BR~10^{-3}), over a 20 times larger BG.
- But full mass reconstruction possible, and for these masses Higgs is a very narrow resonance (Ecal energy and pointing resolution essential!)





Results from data

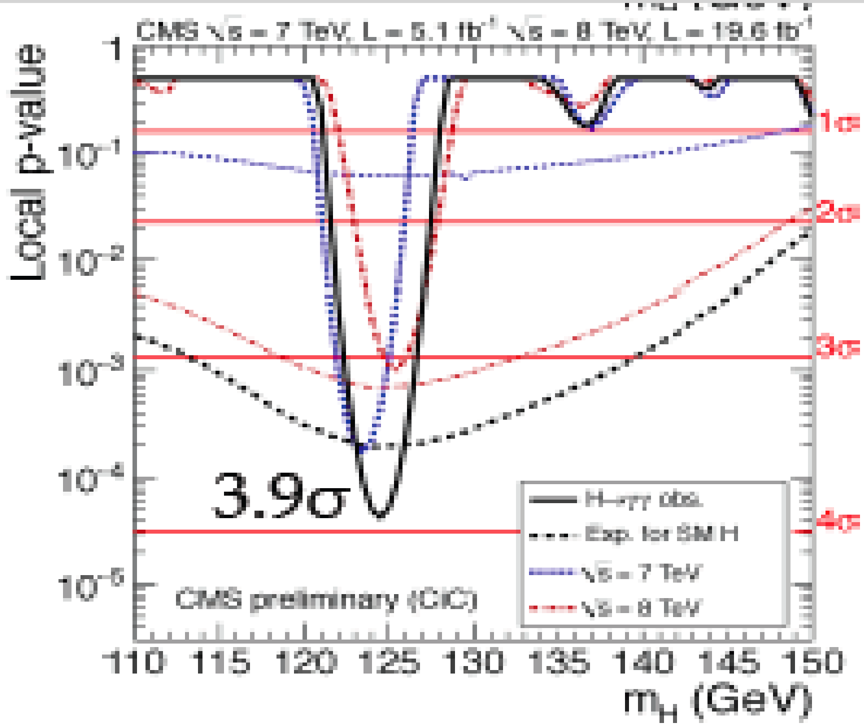


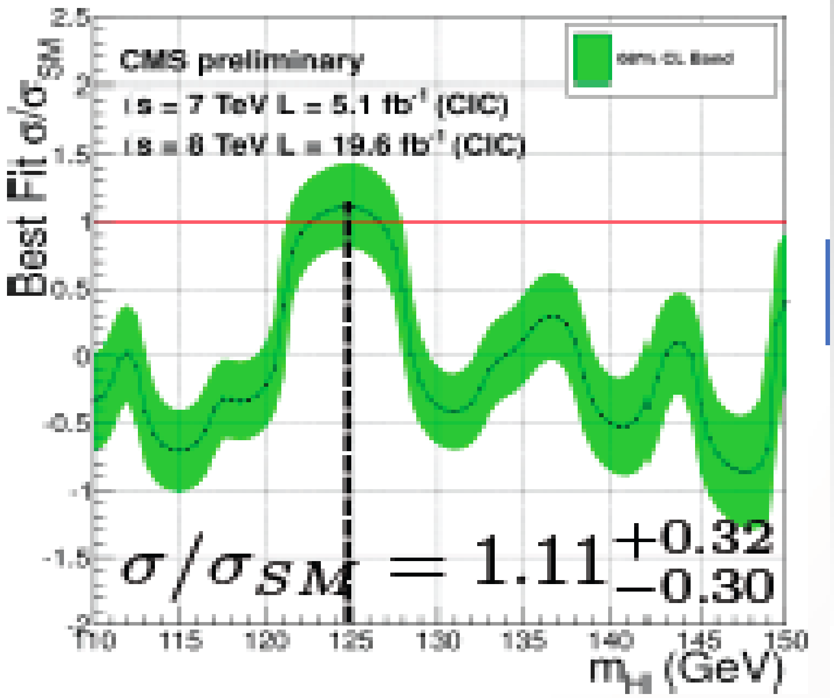


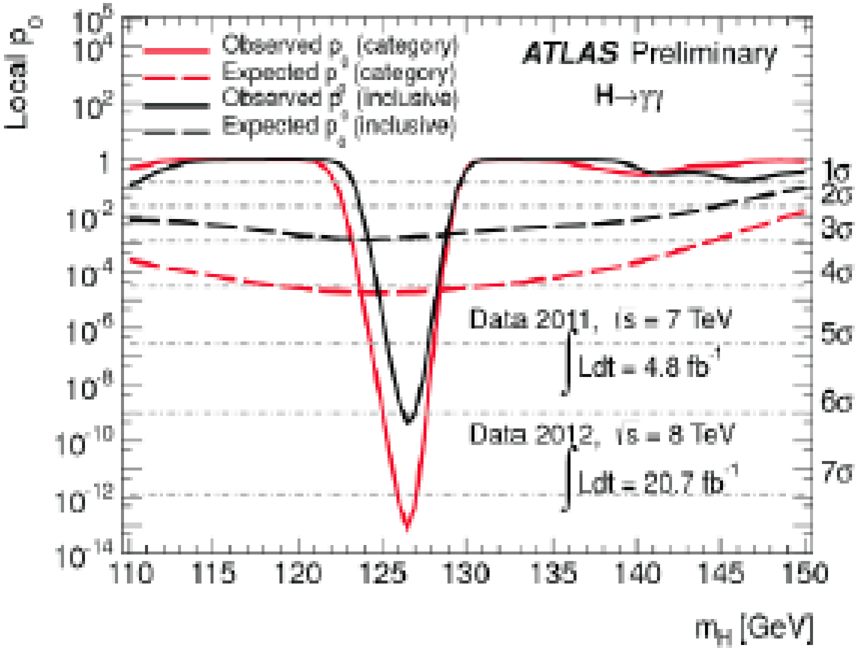
Despite complementary detector technologies, and resolutions (better in energy for CMS, better in angle for ATLAS), width and strength of observed peaks are the same!

Signal strength from this channel

Cut Based



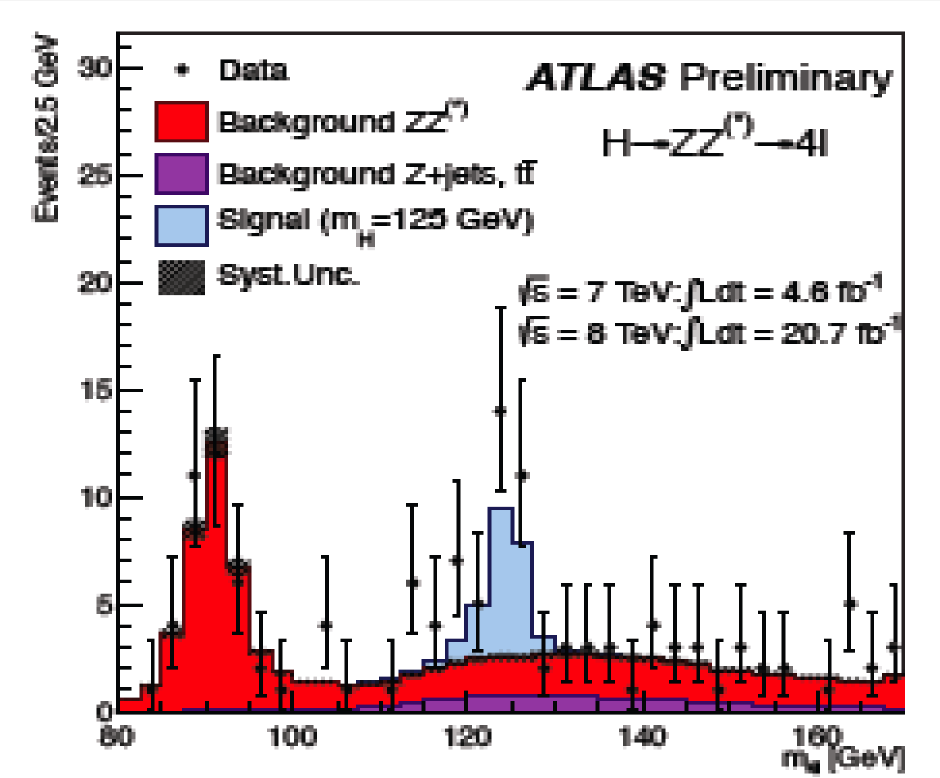


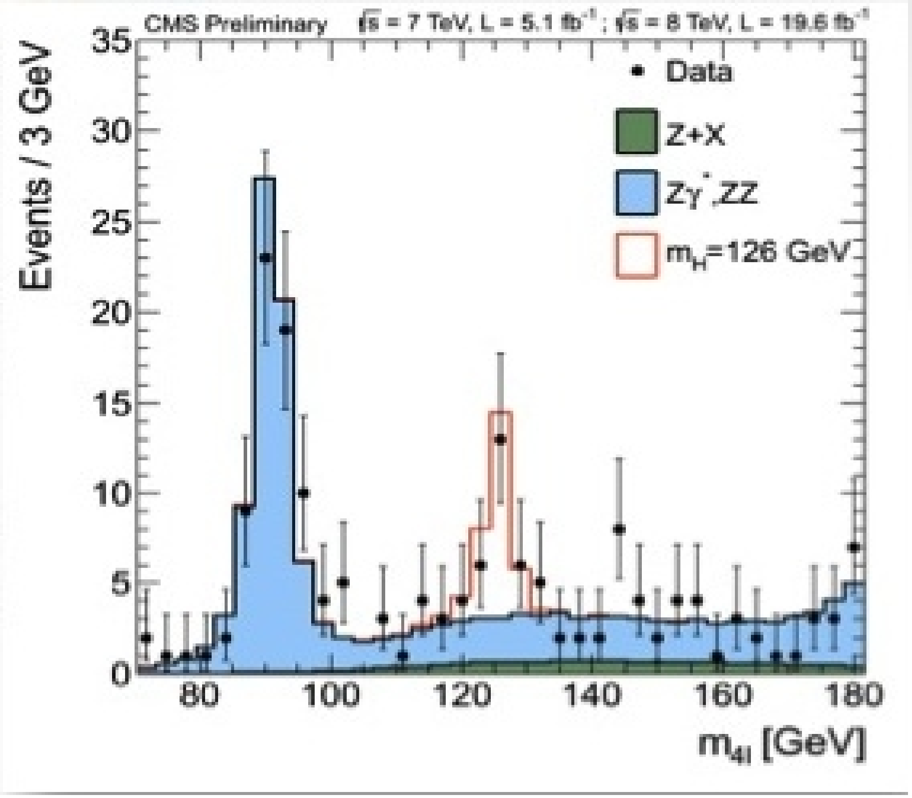


Similar signal in both experiments, with a σ*BR now in agreement with SM after initial larger vlue

Higgs → four charged leptons

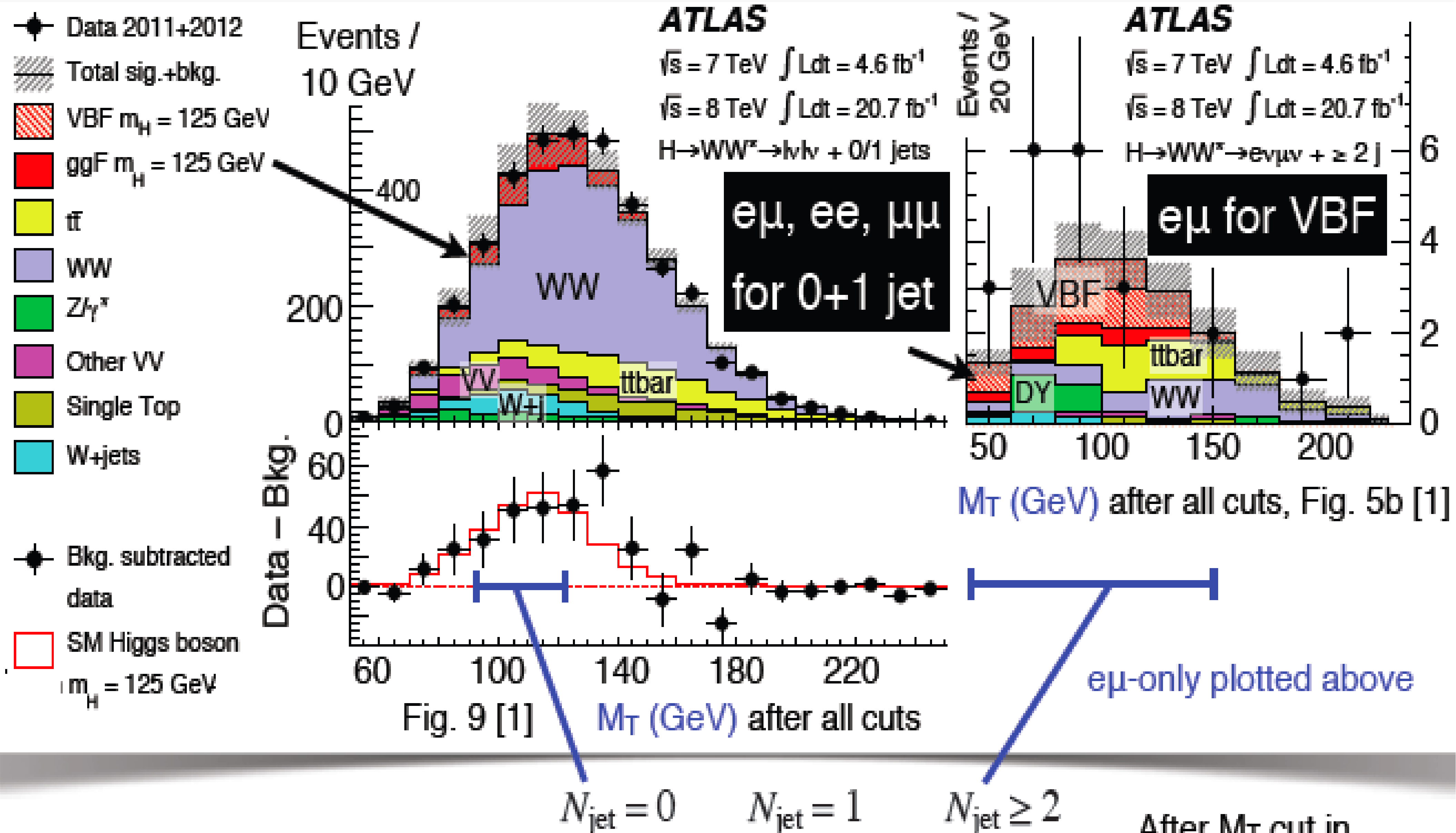
- Golden channel if mass is >2 Mz, it still plays a role at low masses. Small σ*BR: 2.5 fb





Z->ZZ* peak used to cross-check efficiencies, calibrations etc.

WW channel: no peak, look at MET distribution



eμ, ee, μμ for 0+1 jet

eμ for VBF

Fig. 9 [1] M_T (GeV) after all cuts

M_T (GeV) after all cuts, Fig. 5b [1]

eμ-only plotted above

After M_T cut in

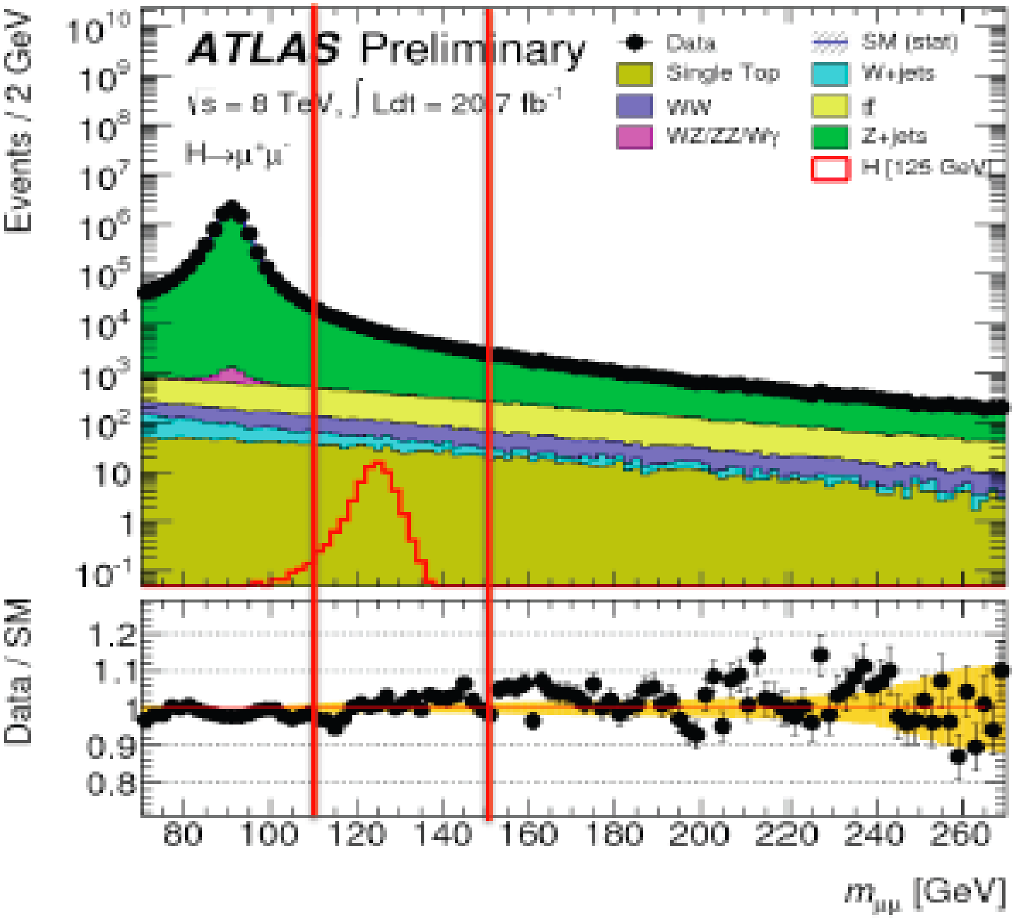
Decays to fermions

- Evidence of coupling to fermions so far
  - **Tevatron VH(→bb) combination:** 2.8σ excess @ M_H=125 GeV
  - **CMS VH(→bb):** 2.1σ excess @ M_H=125 GeV
  - **CMS H→ττ:** 2.85σ excess @ M_H=125 GeV
    - CMS H→ττ and H→bb combination: 3.4σ excess @ M_H=125 GeV
- Search for H→fermions decays is one of the most important goals for the Higgs program
  - In particular, does Higgs couple to leptons?
    - We already indirectly know that it couples to quarks
  - Are $\Gamma_{H\to ff}$ consistent with SM predictions?
  - Is it the same Higgs decaying to H→VV & H→ff?
    - Is mass the same? CP properties?

$$\Gamma_{H\to ff} = \frac{N_C M_H}{8\pi v^2} m_f^2 \beta_f^3, \quad \beta_f = \sqrt{1 - \frac{4m_f^2}{M_H^2}}$$

H→μμ Search: Analysis Overview

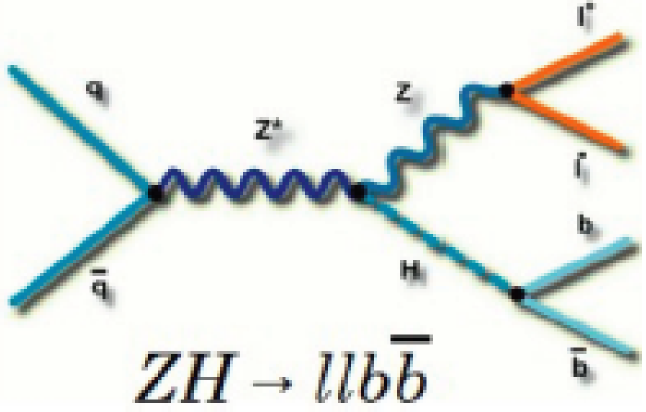
- Analysis strategy
  - Inclusive search
  - **Fit M(μμ) with analytic Signal +Bckg shape**
  - Two analysis categories based on muon resolution:
    - Central: |η(μ1,2)|<1.0
    - Non-central: rest
- Event selection for signal region
  - Single muon trigger
  - Two isolated opposite-sign muons
  - $P_T(\mu 1)>25$ GeV, $P_T(\mu 2)>15$ GeV
  - $P_T(\mu\mu)>15$ GeV



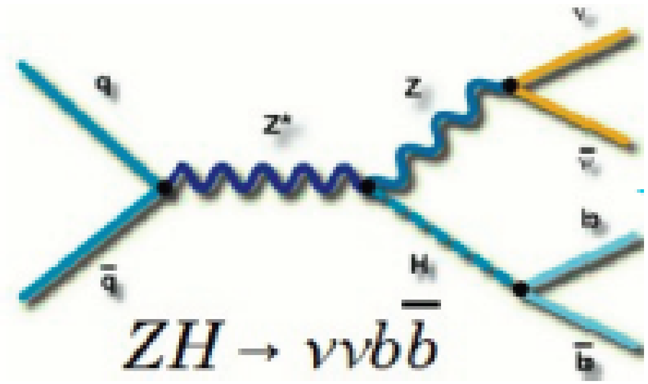
Search window: 110-150 GeV
MC background predictions are not used in the search (for optimization only)

– 95% CL limit on μ @ 125 GeV: expected (μ=0) 8.2×SM, observed 9.8×SM

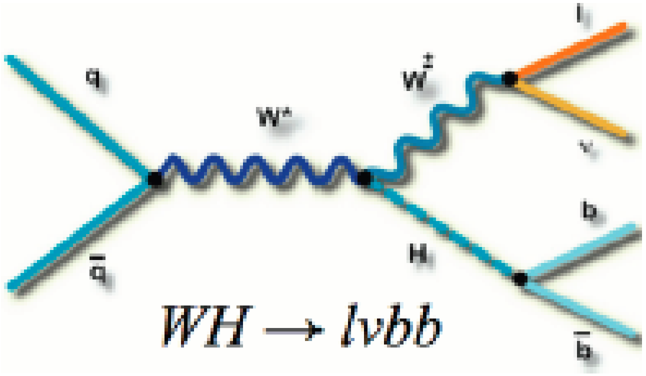
H→bb Search: Exploit Unique VH Production Signature



$ZH \rightarrow llb\bar{b}$



$ZH \rightarrow \nu\nu b\bar{b}$



$WH \rightarrow l\nu bb$

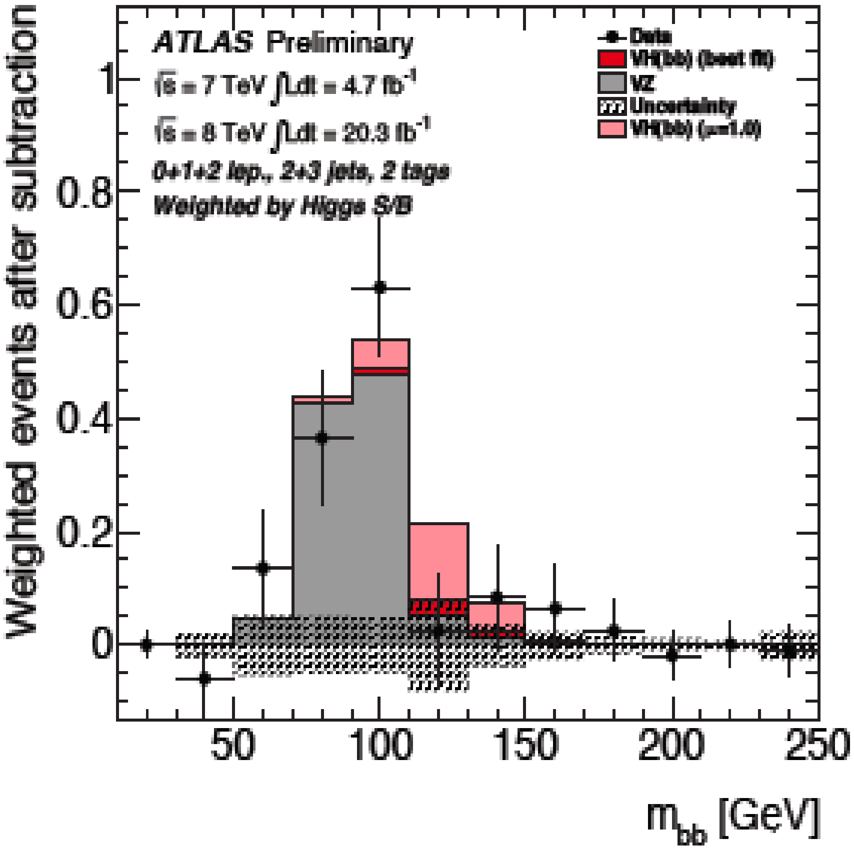
- Cut-based analysis in 3 final states
- ZH→ll+bb
  - **Signature:** two opposite sign leptons and 2 b-tagged jets
  - **Major backgrounds**: Z+ heavy flavor jets
- ZH→νν+bb
  - **Signature:** large MET and 2 b-tagged jets
  - **Major backgrounds**: top, Z/W+ heavy flavor jets
- WH→l+ν+bb
  - **Signature:** one lepton, MET and 2 b-tagged jets
  - **Major backgrounds**: top, W+ heavy flavor jets

H->bb analysis and results

Events separated into 0,1 and 2 leptons, with separate selections and fits. Finally, combined into a mass plot, with a deficit in the Higgs region! (but large errors)

Signal strength

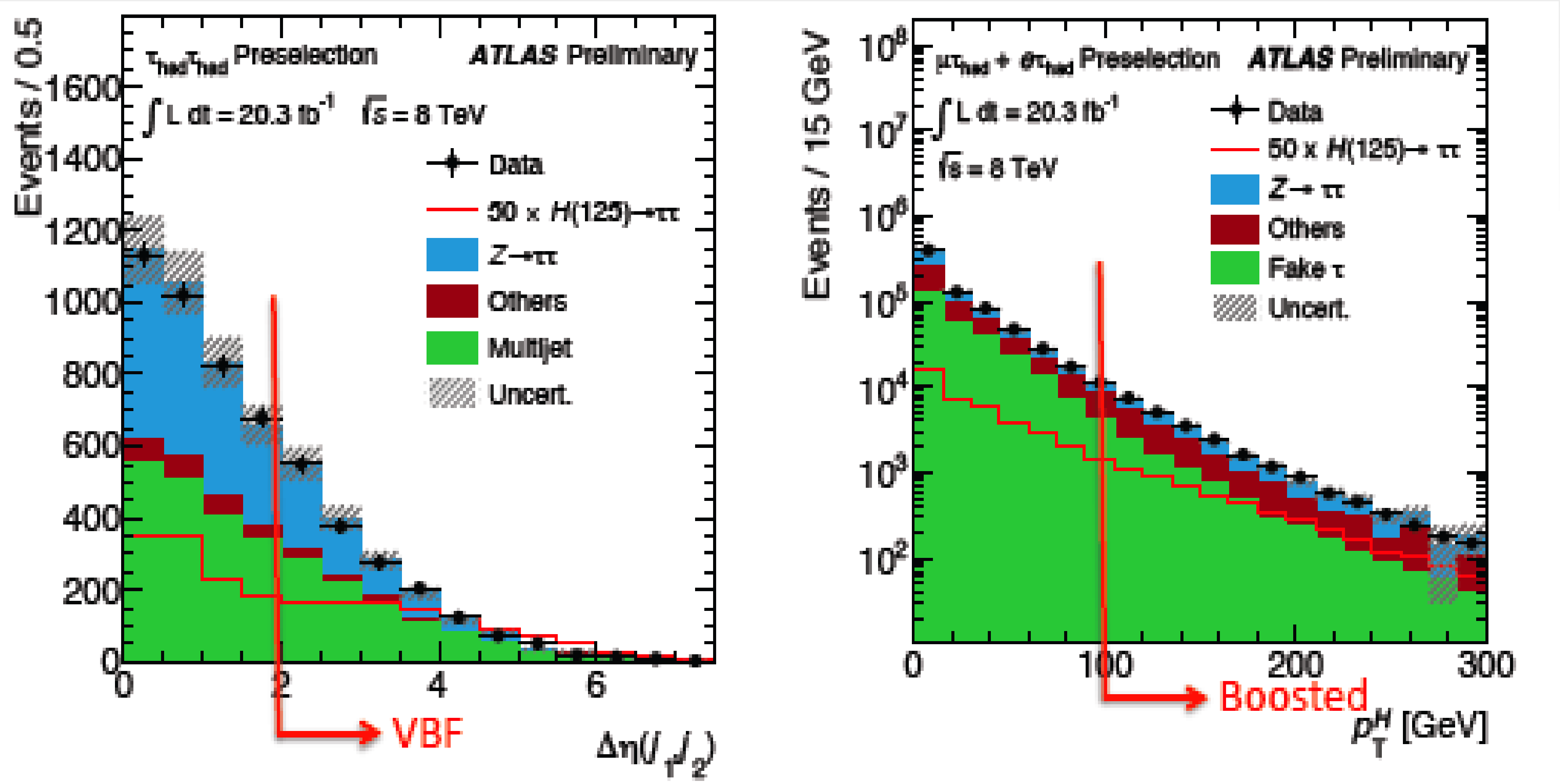
$$\mu_{VZ} = \frac{\sigma^{VZ}_{measured}}{\sigma^{VZ}_{SM}}$$



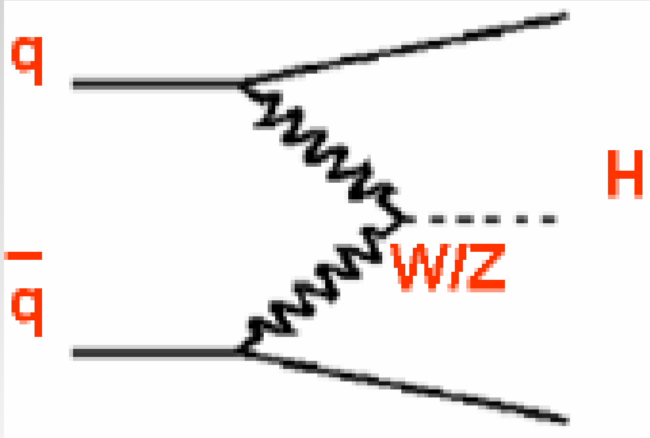
- Measured VZ(→bb) production cross-section is consistent with SM
  - 4.8σ significance; μ_{VZ}=0.9±0.2
  - Same signature as VH(→bb) allows for direct test of analysis procedure

H->ττ in ATLAS

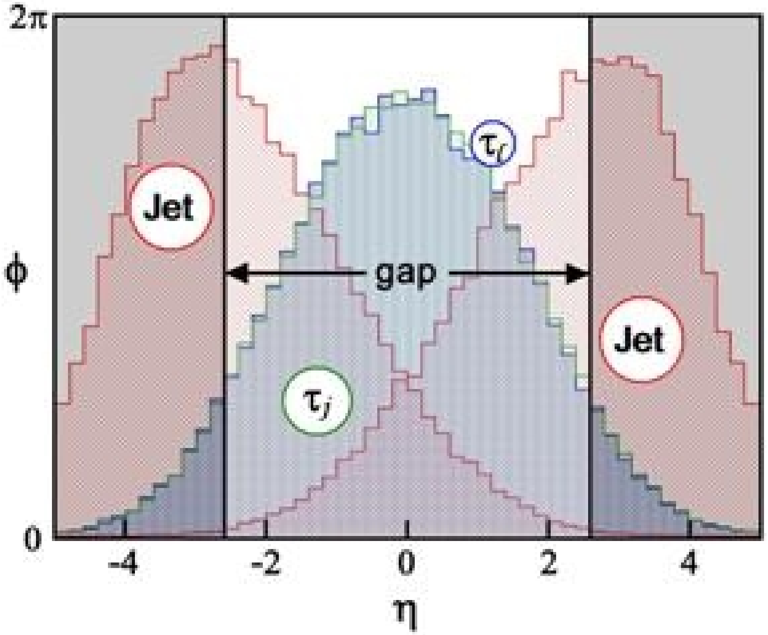
Look independently at three decay modes (ll, lh and hh) as well as different kinematic configurations:



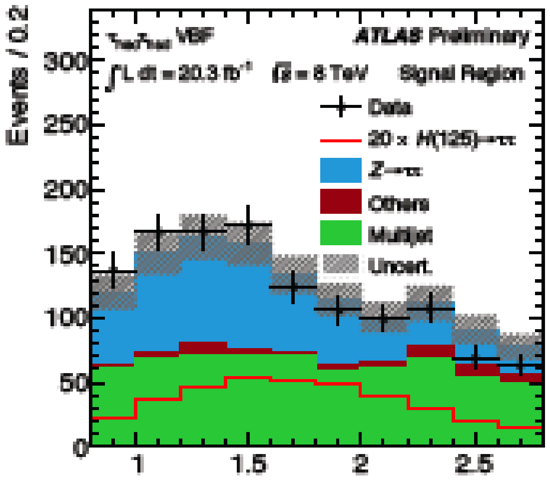
Vector Boson Fusion (VBF)



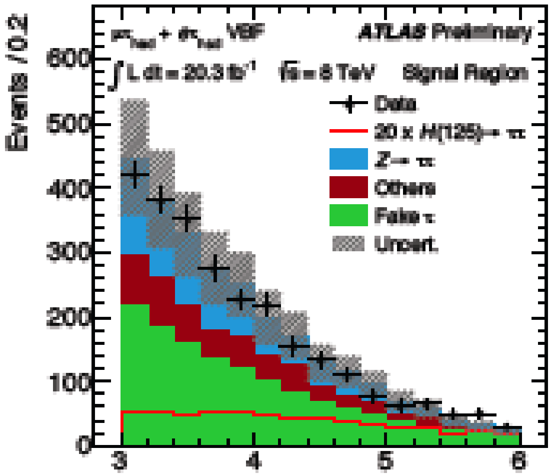
- Remnants of the final-state quarks emitted in the forward region (up to $\eta \sim 3.5$)
- Hard scattering has no colour flow between the two jets → rapidity gap between them
- It would be a very clean signature, if not for the UE and pileup!
- Depending on mass, look for $\tau\tau$ or WW decays



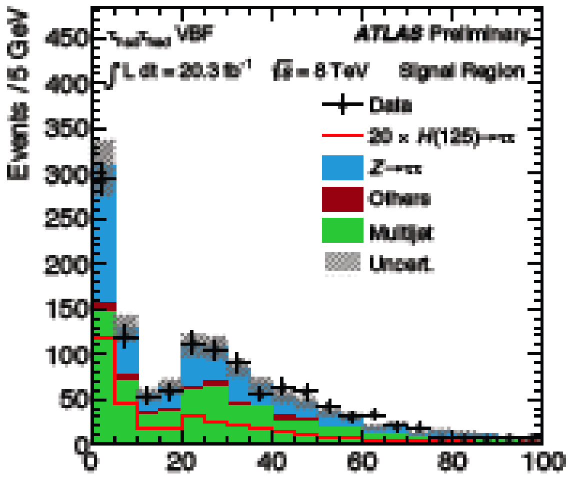
H→ττ Search: Input Variables to BDT



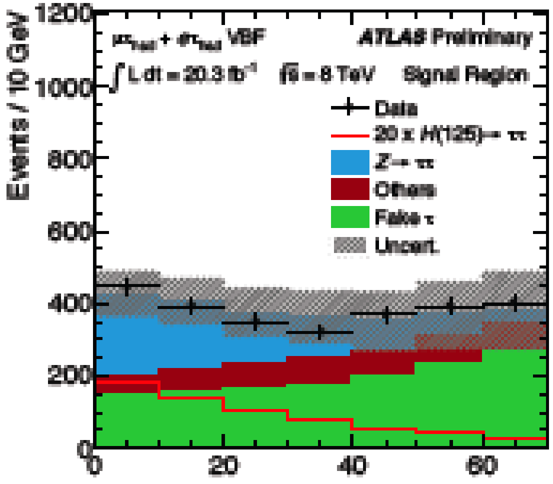
ΔR(ττ)



Δη(jj)



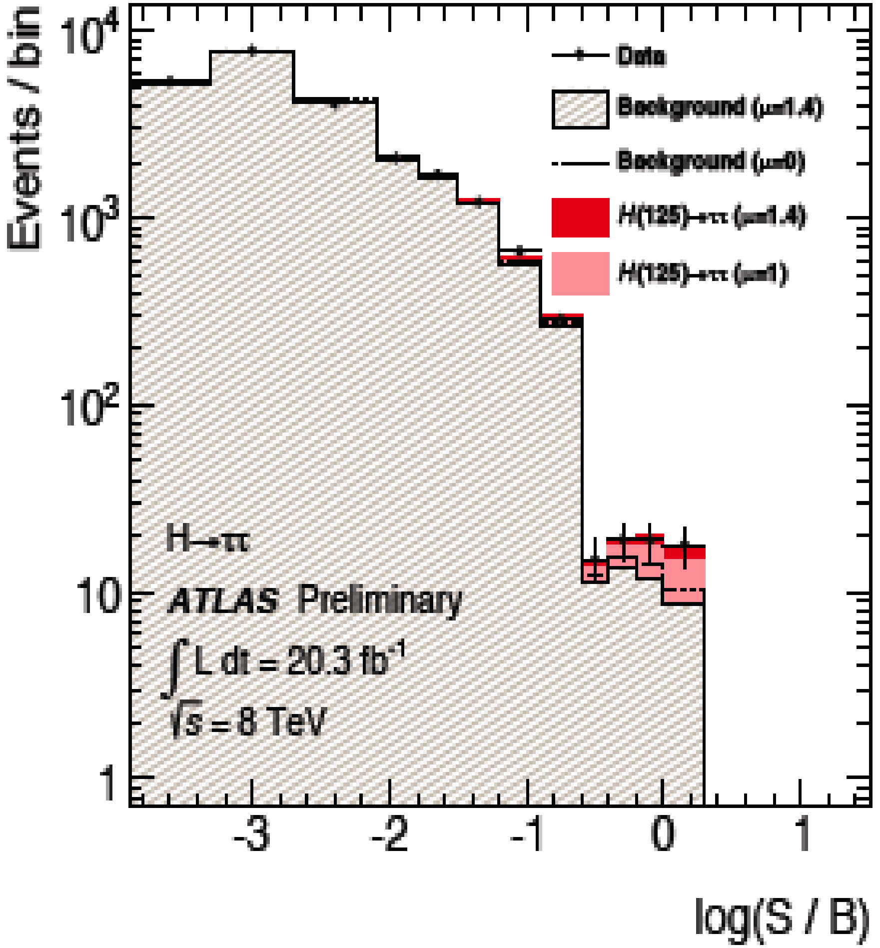
Vector sum P_T



M_T

- Resonance properties
  - m(ττ), ΔR(ττ), etc
- VBF topology
  - m_{jj}, $\Delta\eta_{jj}$, etc
- Event activity
  - Scalar & vector P_T-sum
- Event topology
  - m_T, object centralities, $P_T(\tau_1)/P_T(\tau_2)$, etc
- Number of variables
  - VBF: 7-9
  - Boosted: 6-9

H→ττ Search: Results

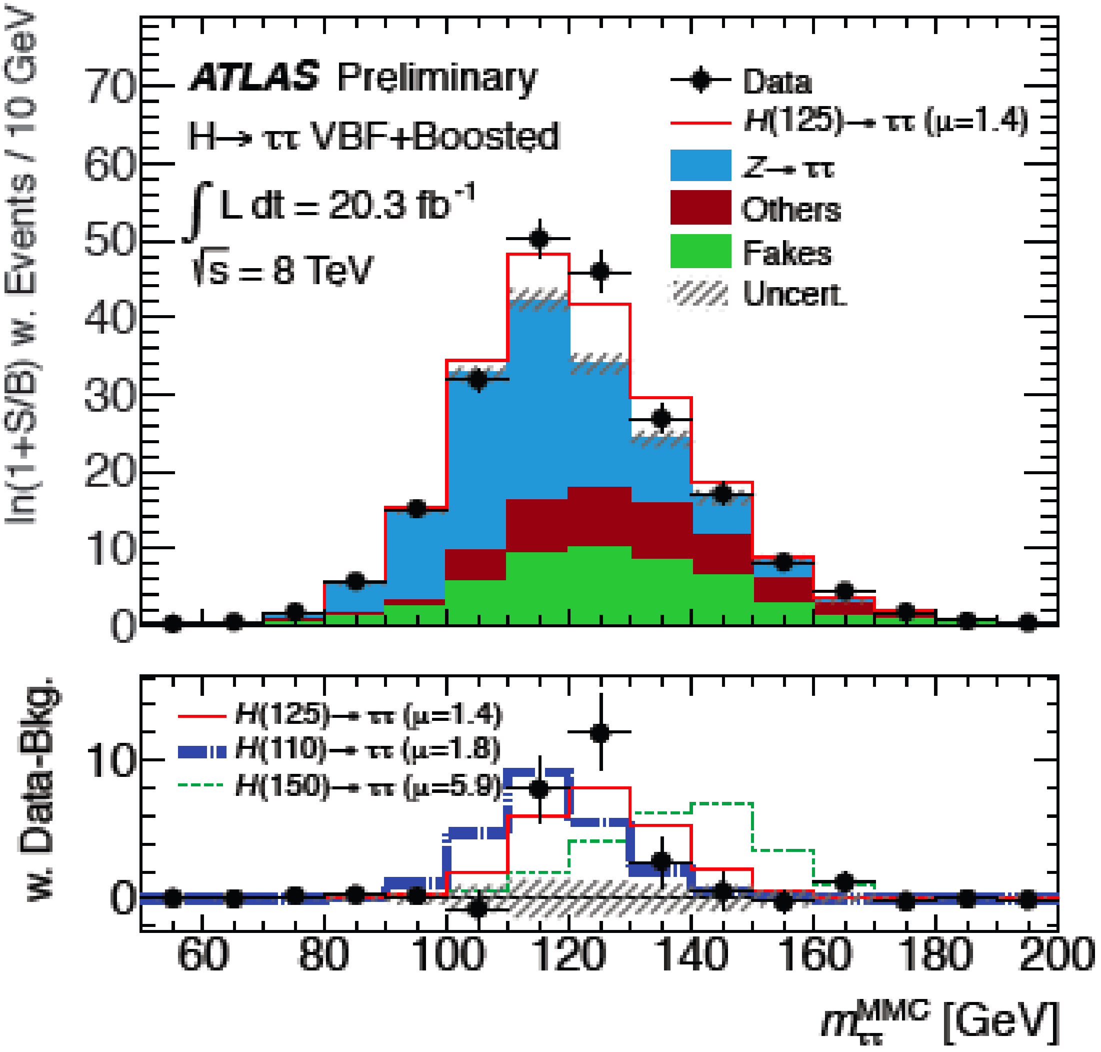


Numbers of events in highest BDT-score bin

		Lep-lep	Lep-had	Had-had
VBF	Signal	5.7±1.7	8.7±2.5	8.8±2.2
	Bckg	13.5±2.4	8.7±2.4	11.8±2.6
	Data	**19**	**18**	**19**
Boosted	Signal	2.6±0.8	8.0±2.5	3.6±1.1
	Bckg	20.2±1.8	32±4	11.2±1.9
	Data	20	34	15

- **ATLAS observes significant excess of data events in high S/B region**
  - Excess is observed in all three channels
  - **Expected** significance at M_H=125 GeV corresponds to **3.2 sigma**
  - **Observed** significance at M_H=125 GeV corresponds to **4.1 sigma**

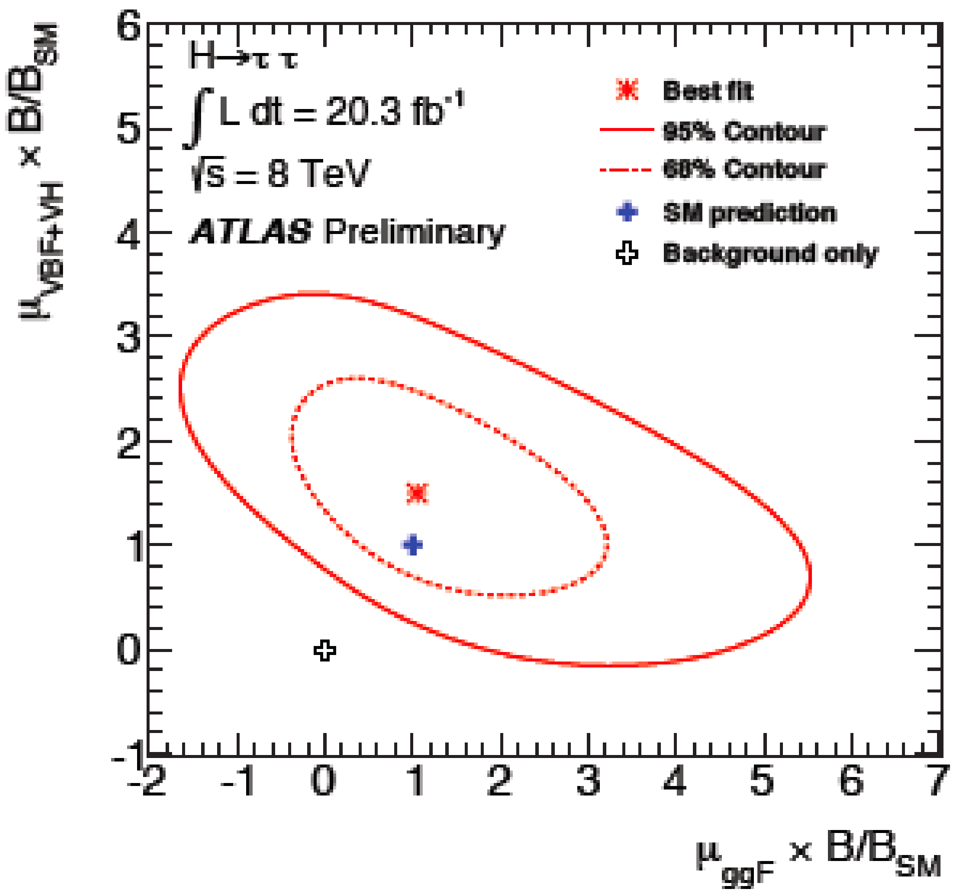
H→ττ Search: Compatibility With M_H=125 GeV



- Each event is weighted by ln(1+S/B) for corresponding bin in BDT-score
- **Excess of data events is consistent with presence of Higgs at 125 GeV**

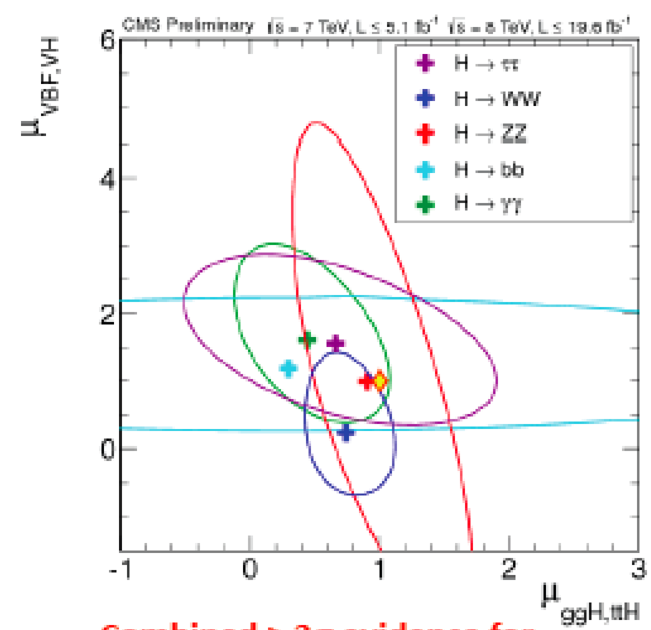
Signals at M_H=110, 125 and 150 GeV are shown at best fit μ; post-fit background normalizations

H→ττ Search: VBF vs Gluon Fusion



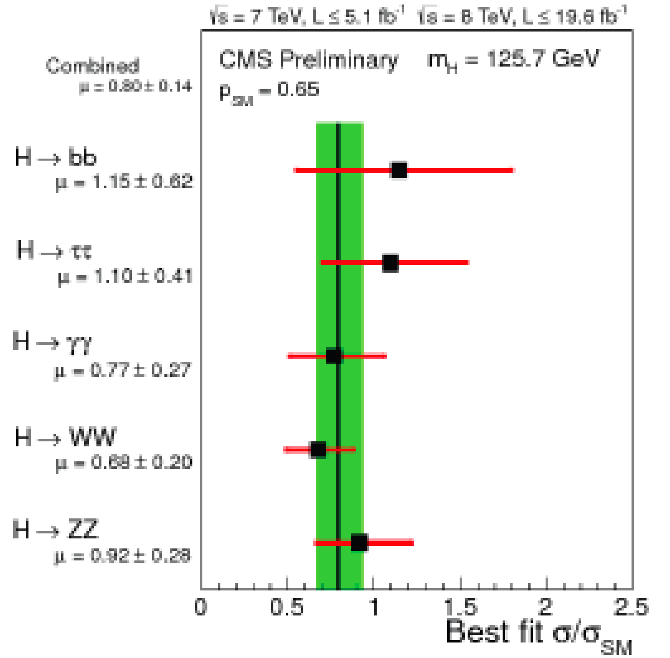
- Results are consistent with SM predictions within 68% contour
- Best fitted values: $\mu_{ggF}\times B/B_{SM}=1.1^{+1.3}_{-1.1}$; $\mu_{VH+VBF}\times B/B_{SM}=1.6^{+0.8}_{-0.7}$

Production and decay modes

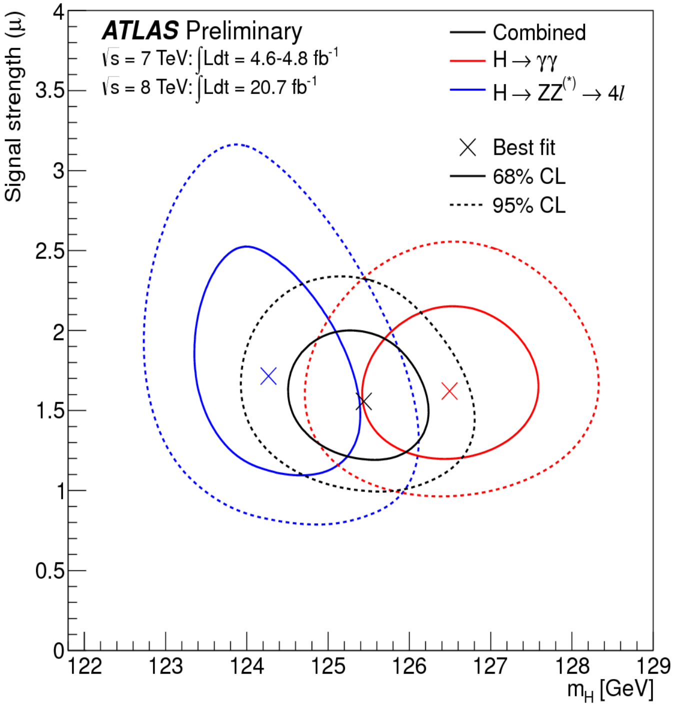


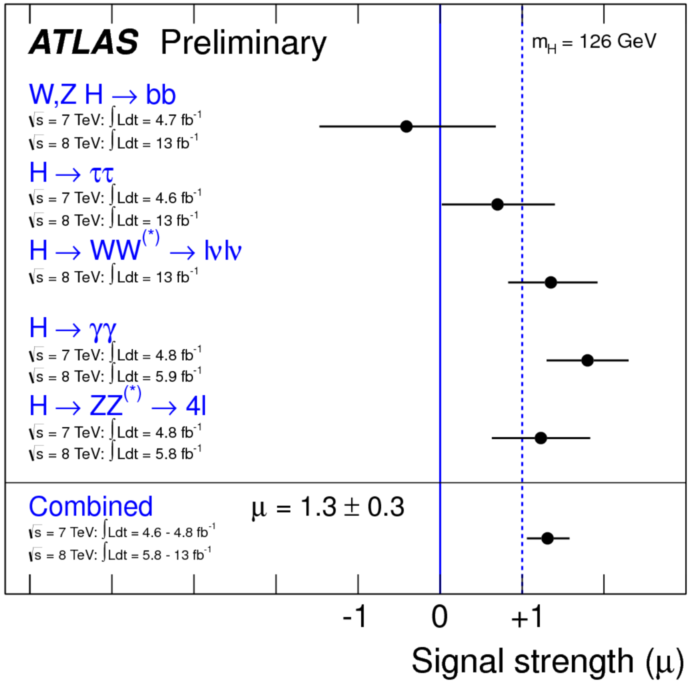
Combined > 3σ evidence for

$\mu_{VBF,VH} / \mu_{ggH,ttH} > 0$

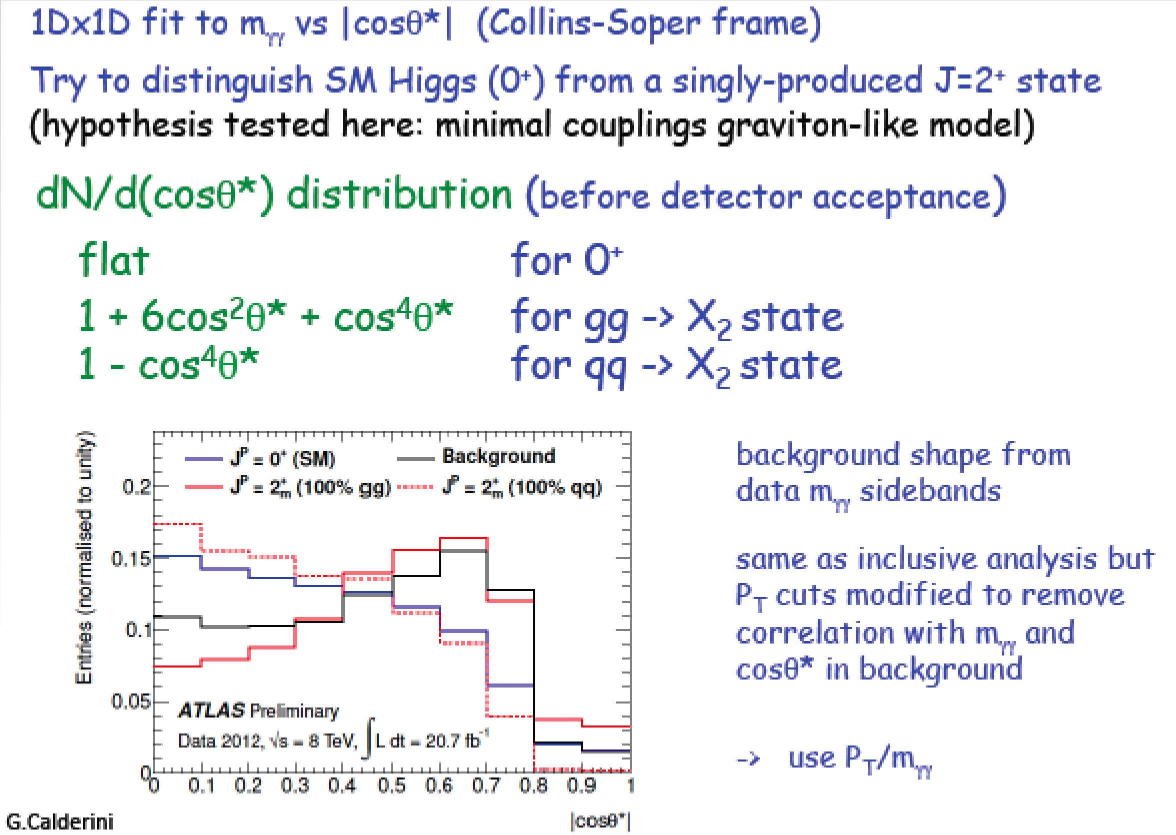


Overall signal strenght $\mu = 0.80 \pm 0.14$





Spin studies



1Dx1D fit to $m_{\gamma\gamma}$ vs $|\cos\theta^*|$ (Collins-Soper frame)

Try to distinguish SM Higgs (0^+) from a singly-produced $J=2^+$ state
(hypothesis tested here: minimal couplings graviton-like model)

dN/d(cosθ*) distribution (before detector acceptance)

flat	for 0^+
$1 + 6\cos^2\theta^* + \cos^4\theta^*$	for gg -> X_2 state
$1 - \cos^4\theta^*$	for qq -> X_2 state

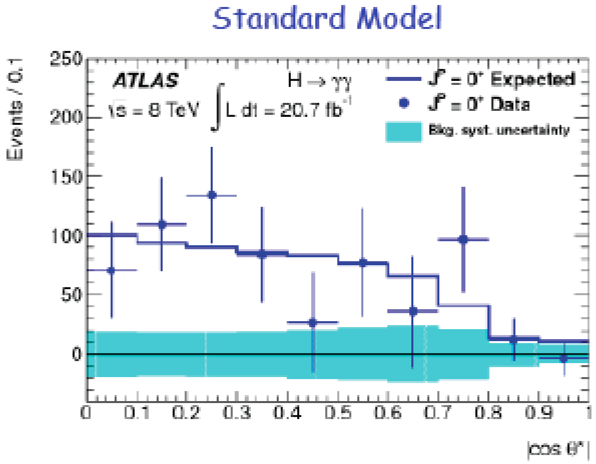
background shape from data $m_{\gamma\gamma}$ sidebands

same as inclusive analysis but P_T cuts modified to remove correlation with $m_{\gamma\gamma}$ and cosθ* in background

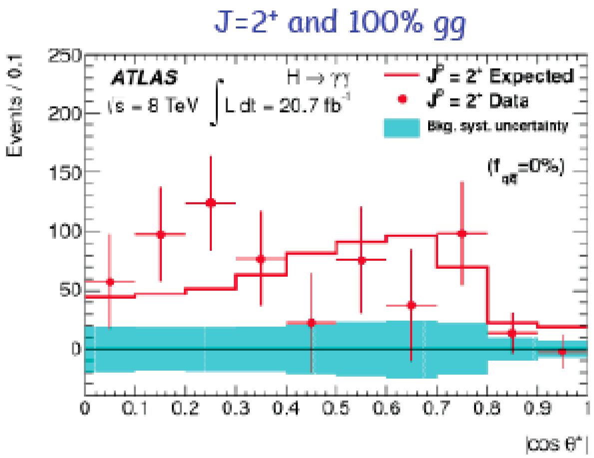
-> use $P_T/m_{\gamma\gamma}$

G.Calderini

- About 60% probability of SM compatibility

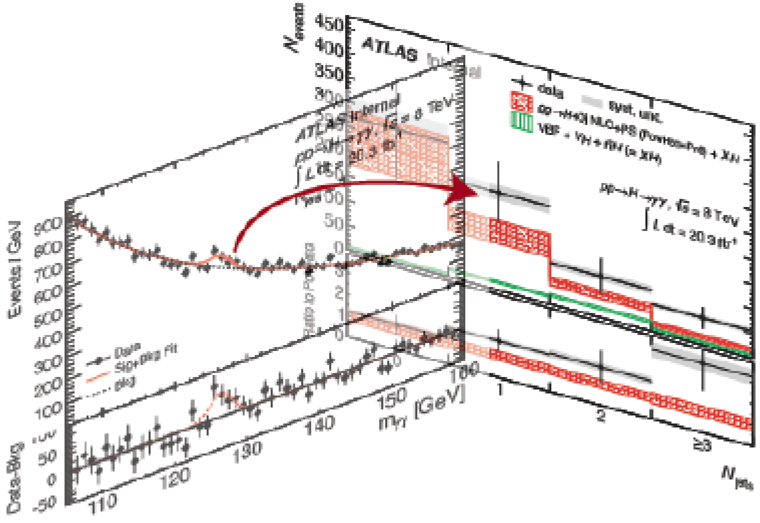


Standard Model



J=2⁺ and 100% gg

Differential cross-sections

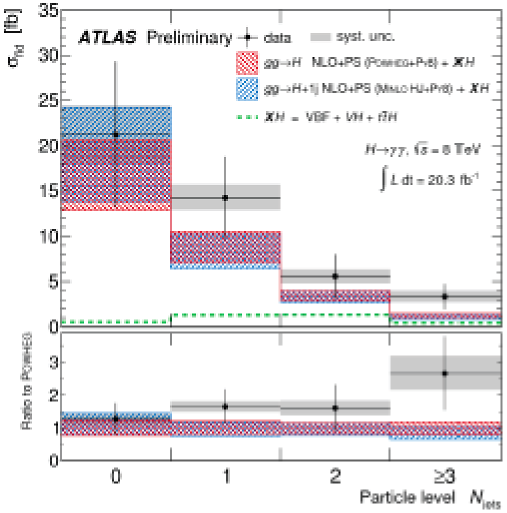


Define a binning for a variable

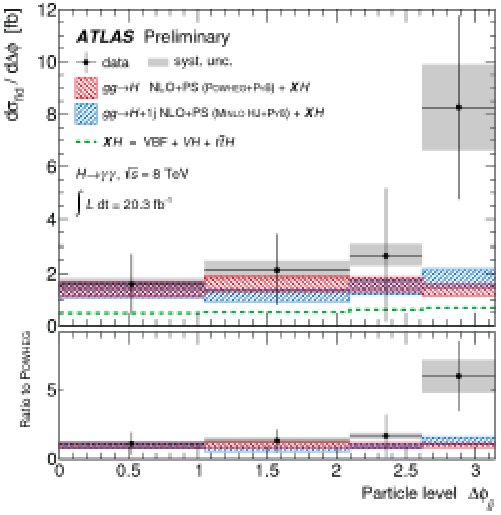
For each bin extract yield from fit to $m_{\gamma\gamma}$

For each bin, correct for acceptance, efficiency, resolution: "*unfolding*"

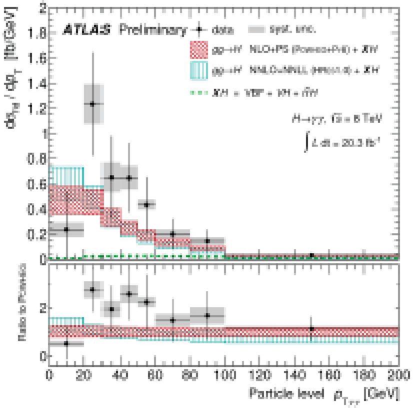
N_{Jet}



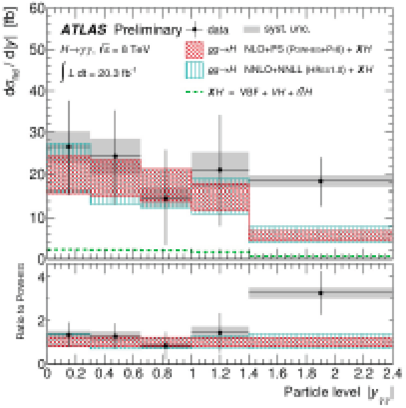
$\Delta\phi_{JJ}$



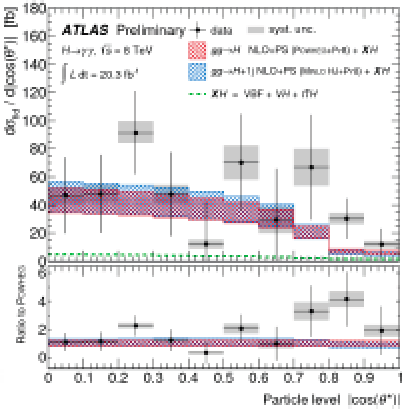
$P_{T\gamma\gamma}$



$\eta_{\gamma\gamma}$



cos θ*



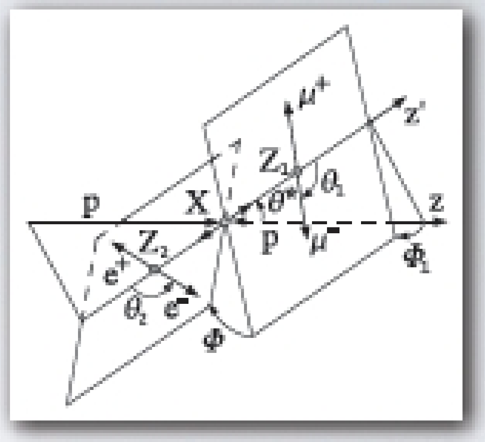
Quantum numbers in H->ZZ

- Use the ratio of **LO** matrix elements to build kinematic discriminants

Discriminator D_{J^P} to separate SM from an alternative J^P hypothesis:

$$D_{J^P} = \left[1 + \frac{\mathcal{P}_{J^P}(\vec{p}_i)}{\mathcal{P}_{\rm Higgs}(\vec{p}_i)} \right]^{-1}$$

Use kinematics of the 4l system

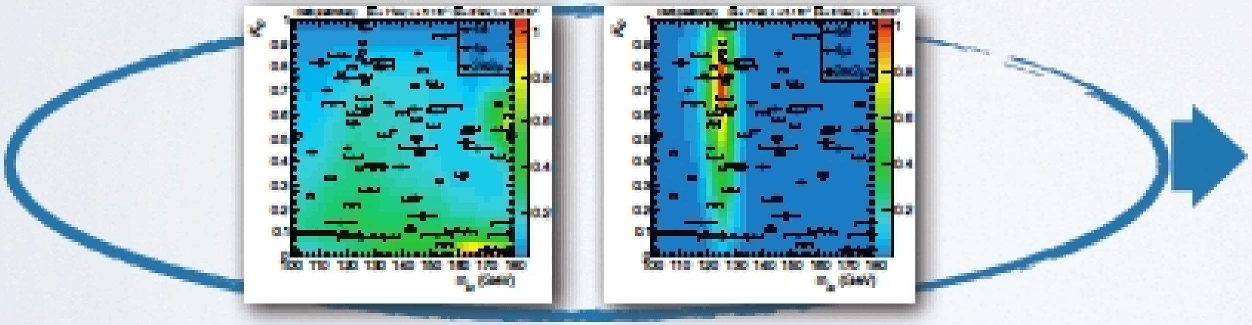


Discriminator D_{BKG} to separate SM Higgs from backgrounds:

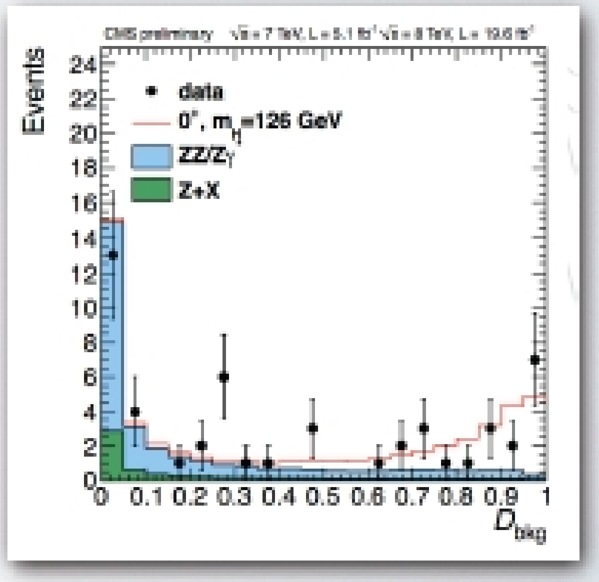
$$D_{\rm BKG} = \left[1 + \frac{\mathcal{P}_{\rm BKG}(\vec{p}_i) \cdot \mathcal{P}(m_{4\ell}|{\rm BKG})}{\mathcal{P}_{\rm Higgs}(\vec{p}_i) \cdot \mathcal{P}(m_{4\ell}|{\rm Higgs})} \right]^{-1}$$

Probabilities $\mathcal{P}$ defined by the LO matrix elements for each value of m_{4l}.

Combined kinematics and m_{4l} information into one discriminant



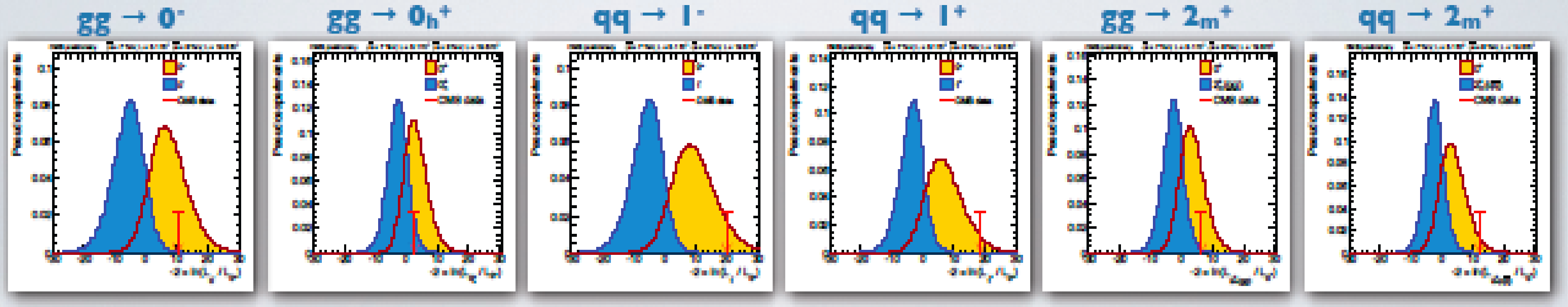
106 < m_{4l} < 141 GeV



- Statistical analysis based on 2D distributions $\mathcal{P}(D_{J^P}, D_{BKG})$

Alternative hipotheses

- Test statistics for the separation between J^P hypotheses (expected and observed):



$gg \to 0^-$ $gg \to 0_h^+$ $qq \to 1^-$ $qq \to 1^+$ $gg \to 2_m^+$ $qq \to 2_m^+$

- Expected separation between J^P hypotheses and the observed results with the data:

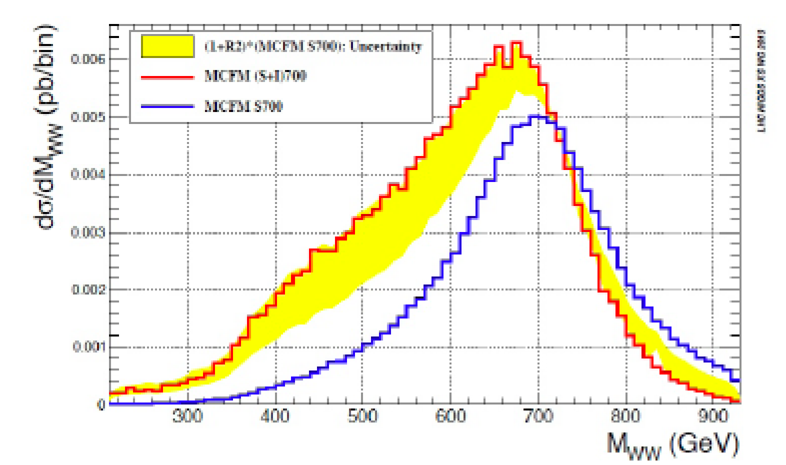
J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	$>4.0\sigma$	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	$>4.0\sigma$	<0.1%

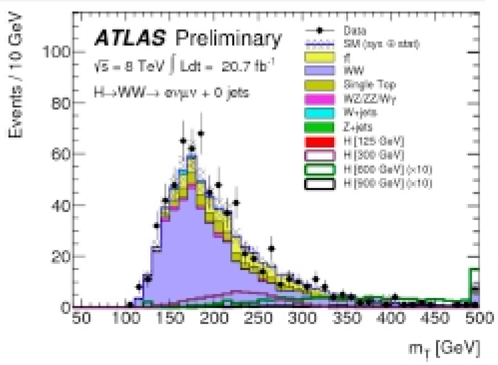
in case a hypothesis is disfavoured with large confidence we quote > 4.0σ,

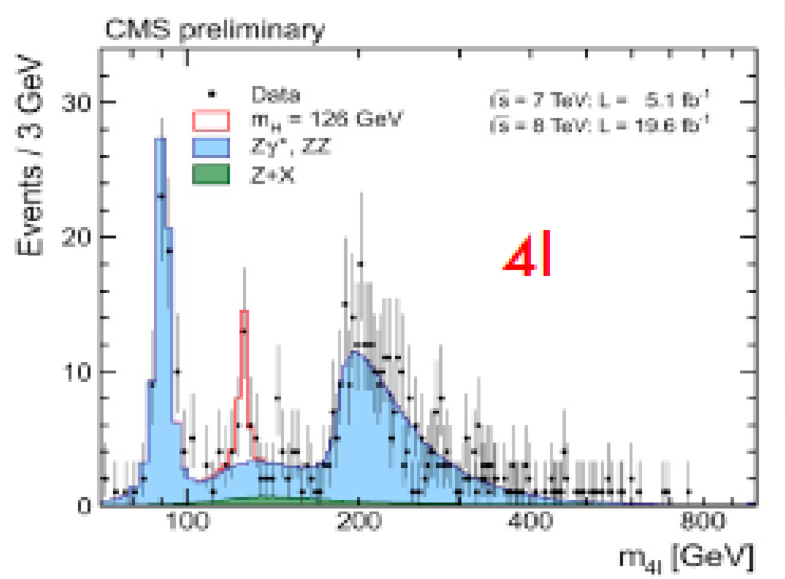
All tested alternative hypotheses (except 0_h^+)
excluded with at least 95% C.L.

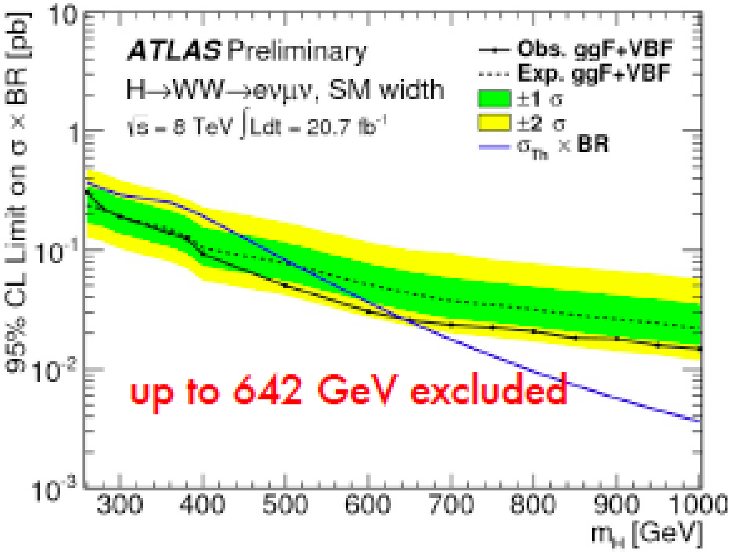
Very high-mass Higgs

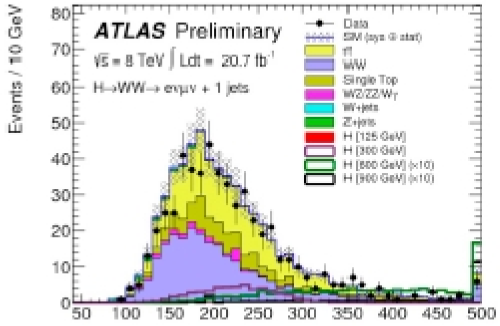
- Even in SM, more than one Higgs can be present, it still makes sense to look for heavy Higgs, and interference

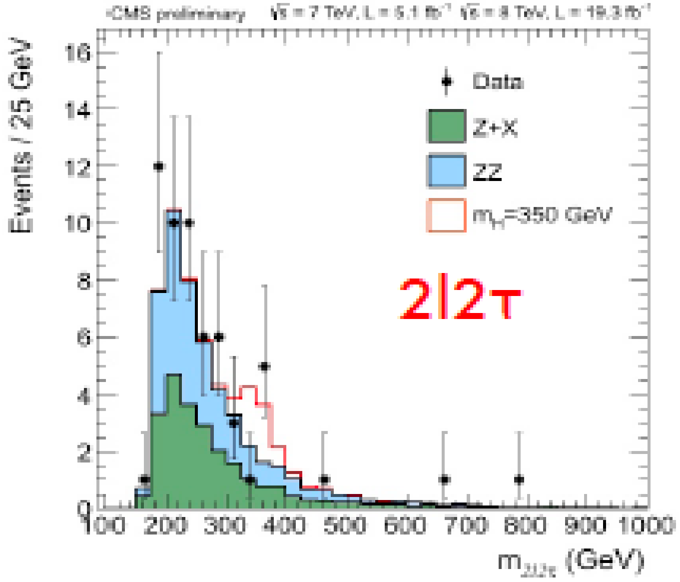






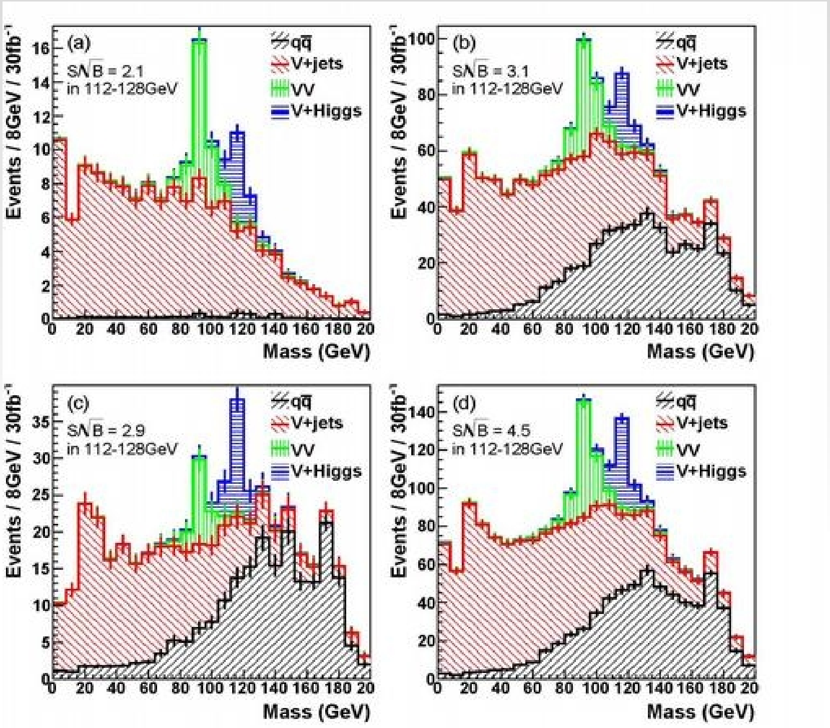




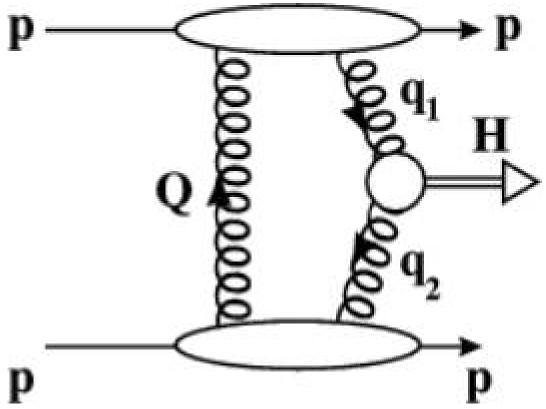


Non-conventional search channels

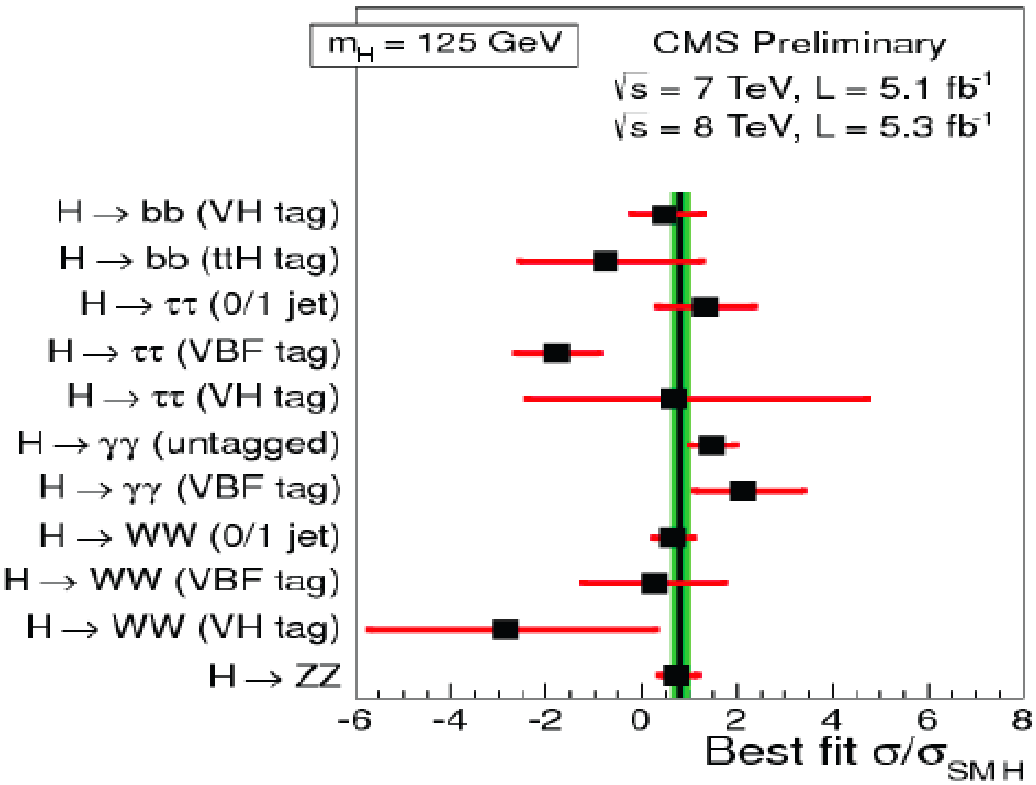
- HZ: S/BG ratio increases for high-Pt Higgs. In that case, and for the main decay channel H->bb, Higgs decay channels end up in a single jet, substructure used to find it

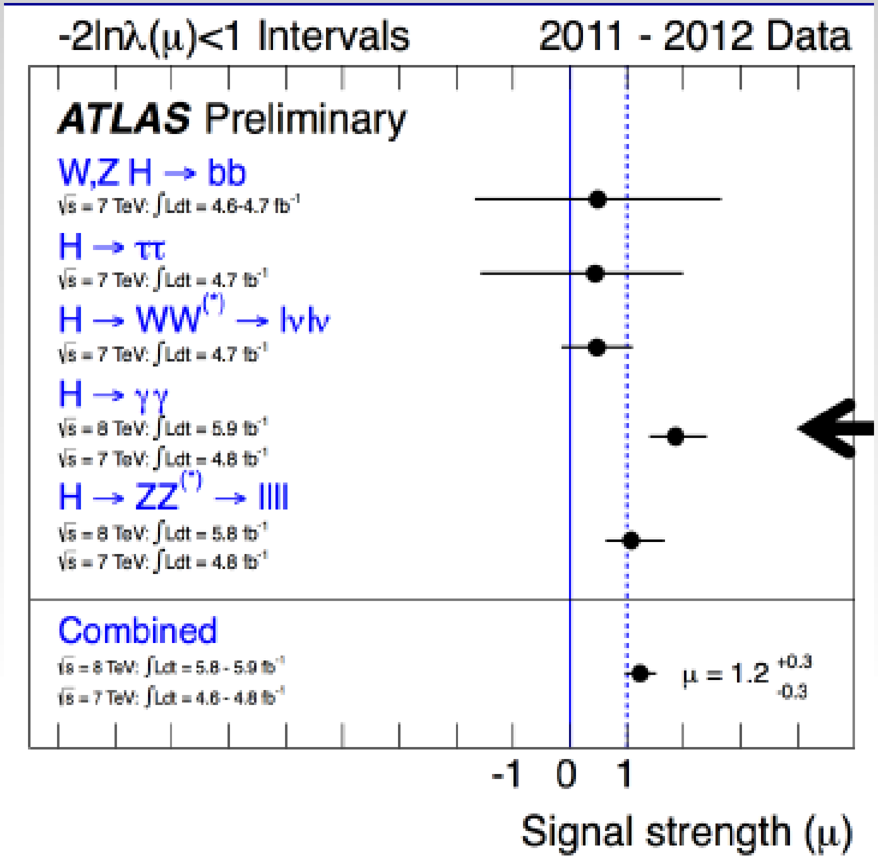


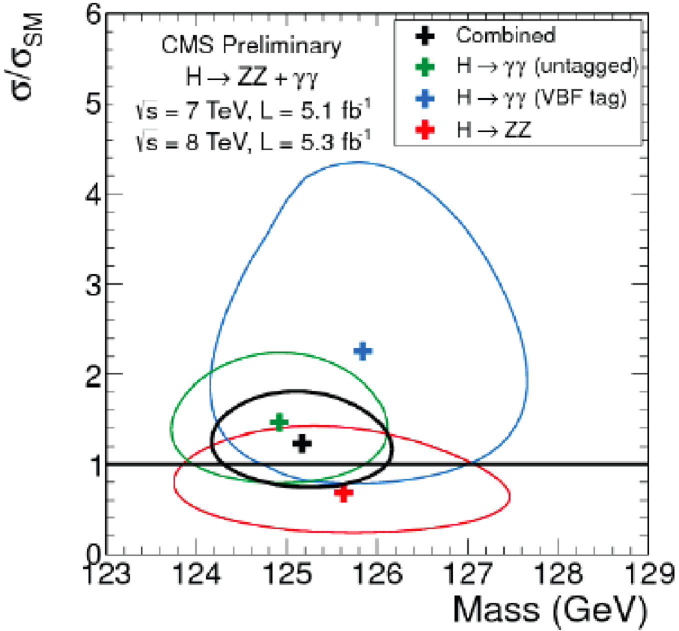
- Diffractive Higgs: Higgs can be produced in diffractive mode, with the two protons stay intact after collision. Only possible with 0^{++} quantum numbers, requires installation of forward proton taggers

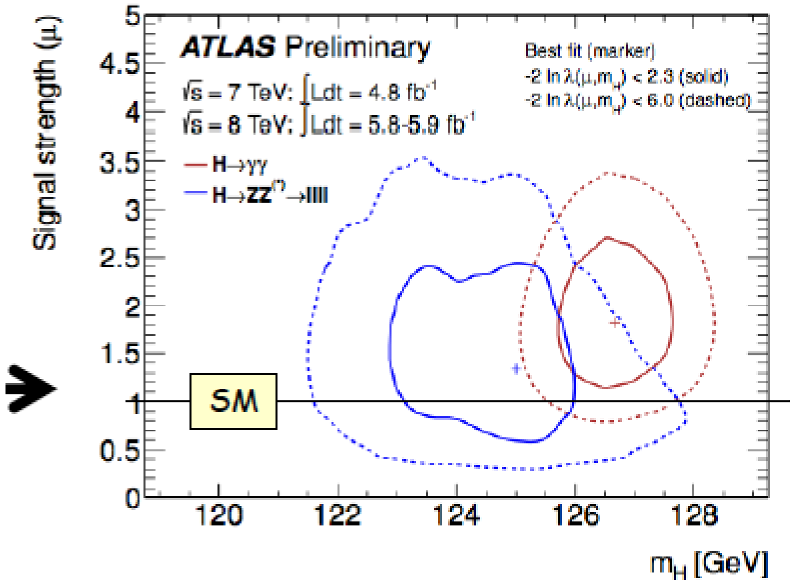


Summary of observations



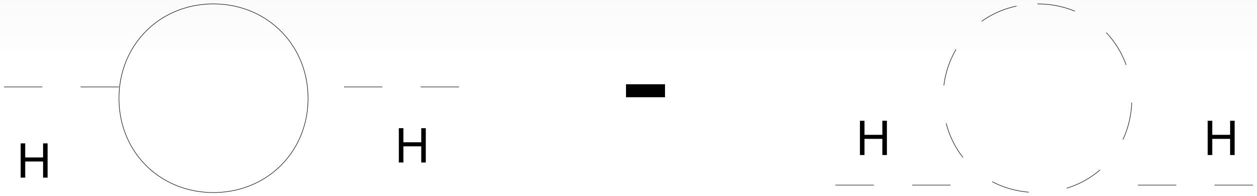






Issues with the Standard Model

- Gravity not included → SM only low-energy effective theory valid to a scale $\Lambda \ll$ Mplank
- The Higgs mass has a loop correcton $\delta m \sim \alpha\Lambda^2$, so to prevent it from becoming super-heavy it requires a compensation or unnatural fine-tuning of parameters

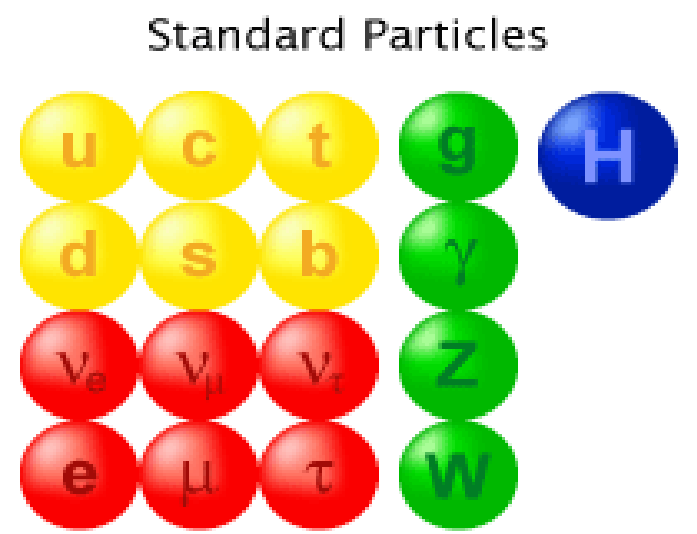


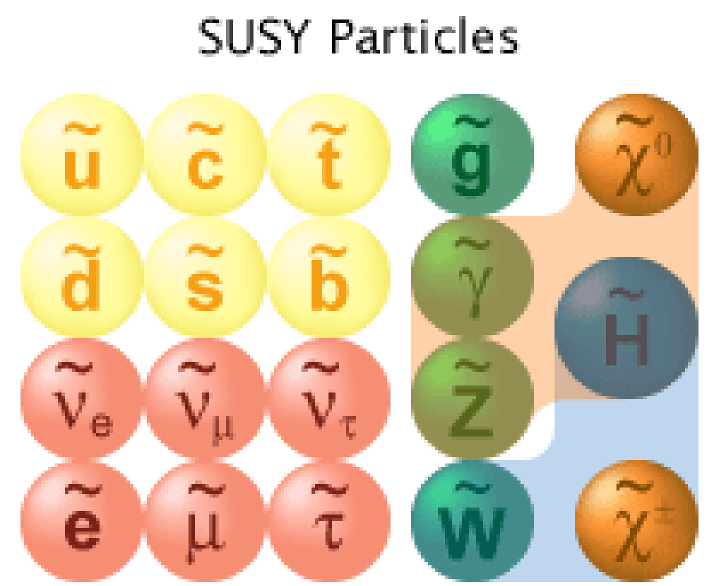
Fermion loop

Boson loop

- Compensation would arise if for each fermion in the loop there was a new boson with similar mass
- This has lead to speculate that the ultimate symmetry of a gauge lagrangian, between fermions and bosons (SUSY) could indeed be realised in nature

Minimal SUSY Standard Model (MSSM) particles





- SUSY equivalants of fermions have prefix s-
- SUSY equicalents of bosons have suffix -ino
- At least two Higgs doublets with lightest Higgs mass < 135 GeV (this can kill SUSY!)
- Charged Higgsinos mix with Winos → charginos
- Neutral Higgsinos mix with Zino/photino → neutralinos

Building a MSSM model

Isospin

$$\begin{pmatrix} P \\ n \end{pmatrix}$$

N = nucleon field

Isospin invariant action

Multiplets of the symmetry transform into one another

Supersymmetry

$$\begin{pmatrix} S \\ \psi \end{pmatrix}$$

$\hat{S}$= Chiral Superfield

SUSY invariant action

- If Hu, Hd, e, u, d, Q, L are the corresponding supermultiplets of SM and SUSY particles:

$$W_{\mathrm{MSSM}} = \overline{u}\mathbf{y}_{\mathbf{u}}QH_u - \overline{d}\mathbf{y}_{\mathbf{d}}QH_d - \overline{e}\mathbf{y}_{\mathbf{e}}LH_d + \boxed{\mu H_u H_d}$$

Dimentioneless yukawa couplings

Hu and Hd give masses to all quarks and leptons (and both are needed)

m-term: SUSY version of the higgs boson from SM

SUSY new particles

SM

SUSY

Eigenstates of mass

Spin 0	Spin 1/2	Spin 1
$\tilde{\chi}_1, \tilde{\chi}_2$	l	
$\tilde{q}_1, \tilde{q}_2$	q	
h0, H0, A0, H±	$\tilde{\chi}^0_1, \tilde{\chi}^0_2, \tilde{\chi}^0_3, \tilde{\chi}^0_4$	
	$\tilde{\chi}^\pm_1, \tilde{\chi}^\pm_2$	γ, Z0, W±
	$\tilde{g}_a$	ga

‘organized’ in super-multiplets

Neutralinos: mass eigenstates of photinos, zinos, neutral higgsinos
Charginos : mass eigenstates of winos and charged higgsinos

Squark/slepton mixing proportional to the SM partner masses

↘ largest for 3rd gen.

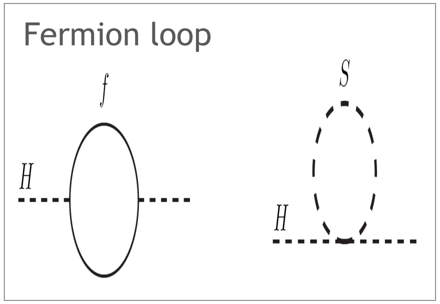
àcan become lightest squarks / sleptons

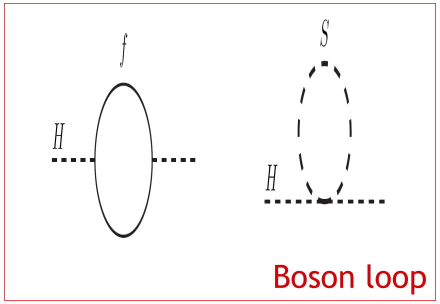
R-parity

- A SUSY particle would have spin ½ smaller than its non-SUSY equivalent (apart from the Higgs!)
- Introduce a new quantity, $R = (-1)^{3(B-L)+2S}$ which is
  - R = +1 for SM particles
  - R = -1 for SUSY particles
- In most SUSY versions R is conserved
  - SUSY particles produced in pairs
  - Lightest SUSY Particle (LSP, usually neutralino) stable, and being weakly interacting typical SUSY signature is missing momentum (also, good candidate for dark matter!)

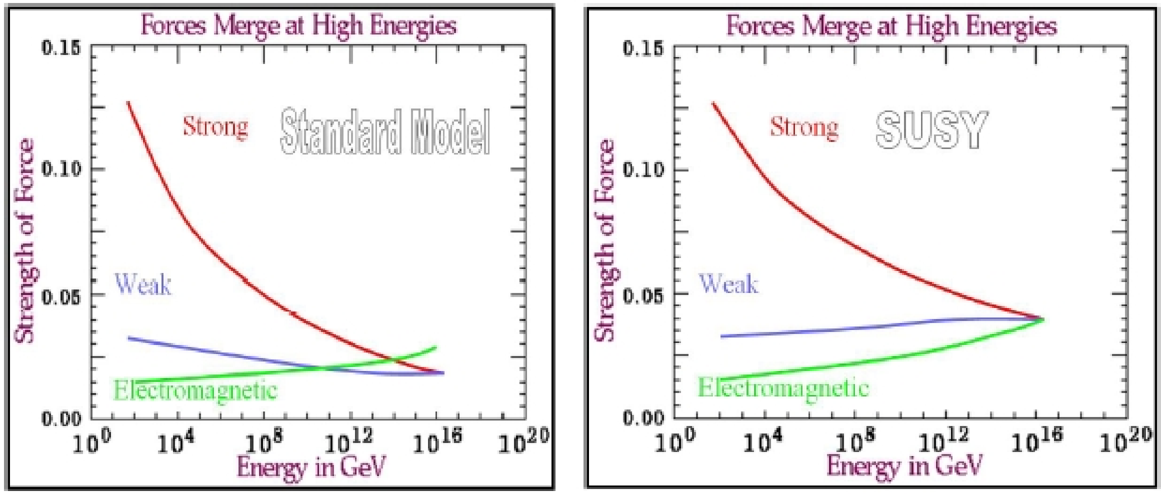
Why people like SUSY

- Predicts a low mass Higgs and naturally solve the hierarchy problem
  - No fine-tuning required

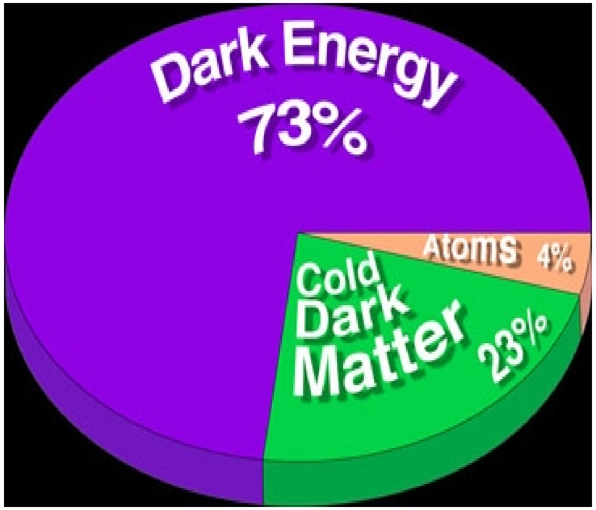




- Enables gauge couplings to unify



Energy (GeV)



- Provides Dark Matter Candidate
  - If R-parity is conserved, the LSP is the perfect candidate

SUSY breaking

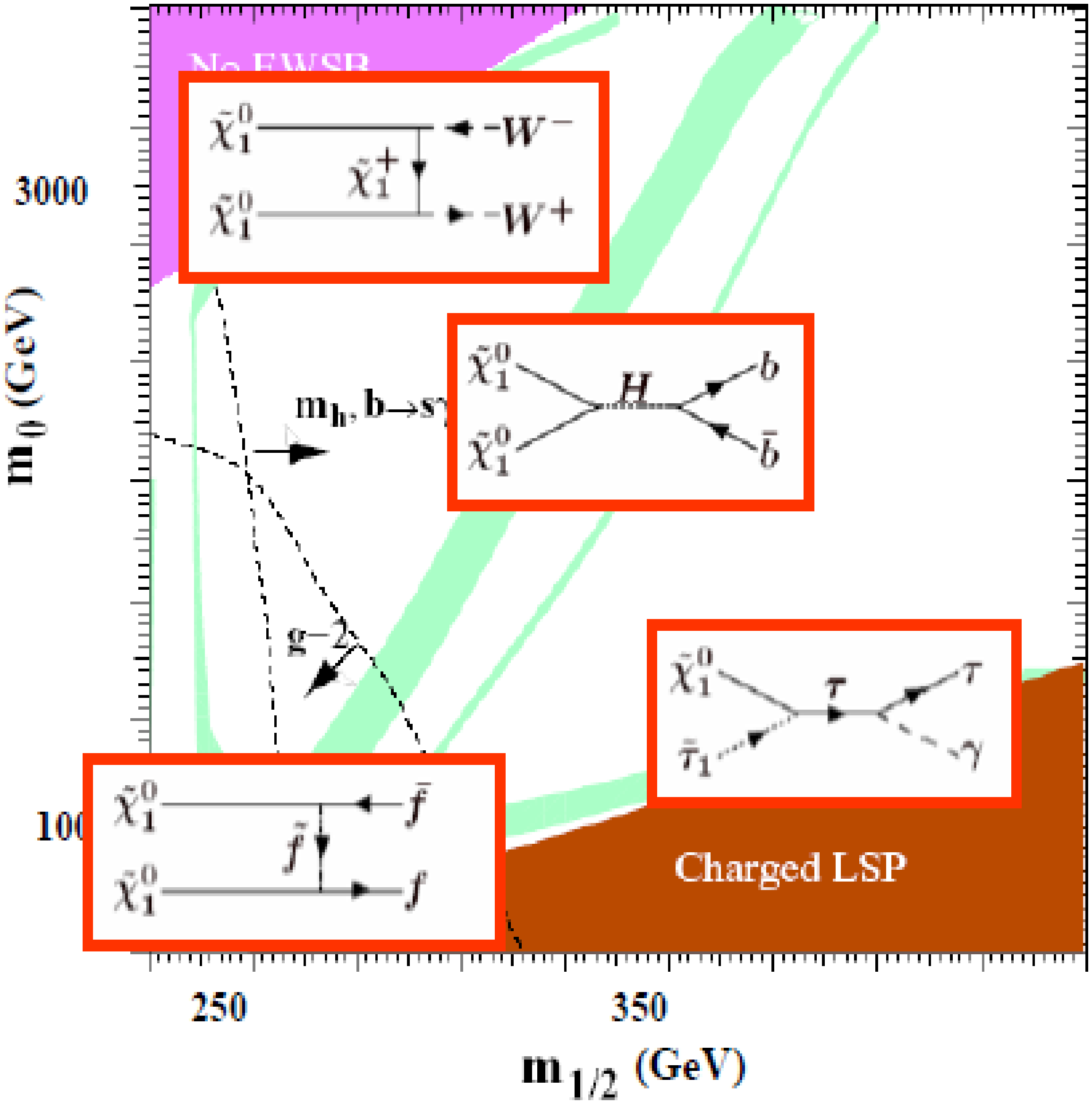
- Since no SUSY particles discovered so far, their masses have to be larger than their SM correspondents. Supersimmetry has to be broken, and spontaneous symmetry breaking does not work (would predict particles lighter than SM correspondents)
- SUSY breaking confined to hidden sector at high scale, and transmitted through flavour-blind interactions:
  - Gravity-mediated (mSUGRA,cMSSM)
  - Anomay-Mediated (AMSM)
  - Gauge-mediated (GMSM)
  - Gaugino-mediated (brane-world scenarios)

A minimal scenario: mSUGRA

- SUSY theories can have a huge number of parameters. To provide benchmark scenarios to compare experimental reach and predictions, some arbitrary assumptions can be made; ex. MSUGRA, with only 5 parameters:
  - m_0 universal scalar mass
  - $m_{1/2}$ mass of all gauginos
  - A_0 trilinear soft breaking term
  - Tan β ratio of vacuum expectation values of Higgses
  - sign(μ) sign of SUSY Higgs mass term (its abs value is the EW symmetry breaking)

MSUGRA parameter space

Four regions compatible with WMAP value for Ωh^2, different mechanisms for neutralino annihilation:



bulk

neutralino mostly bino, annihilation to ff via sfermion exchange

focus point

neutralino has strong higgsino component, annihilation to WW, ZZ

co-annihilation

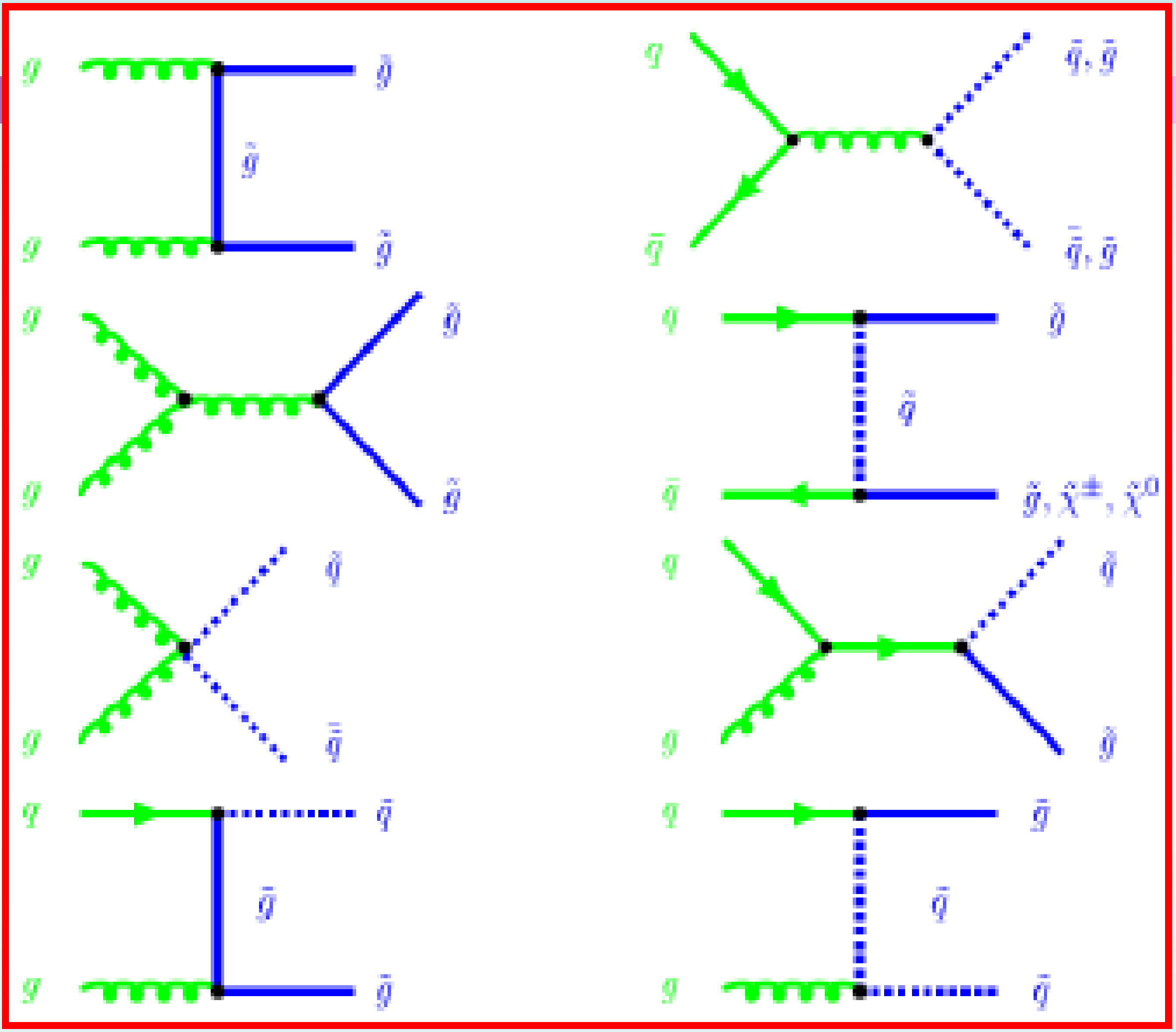
pure bino, small NLSP-LSP mass difference, typically coannihilation with stau

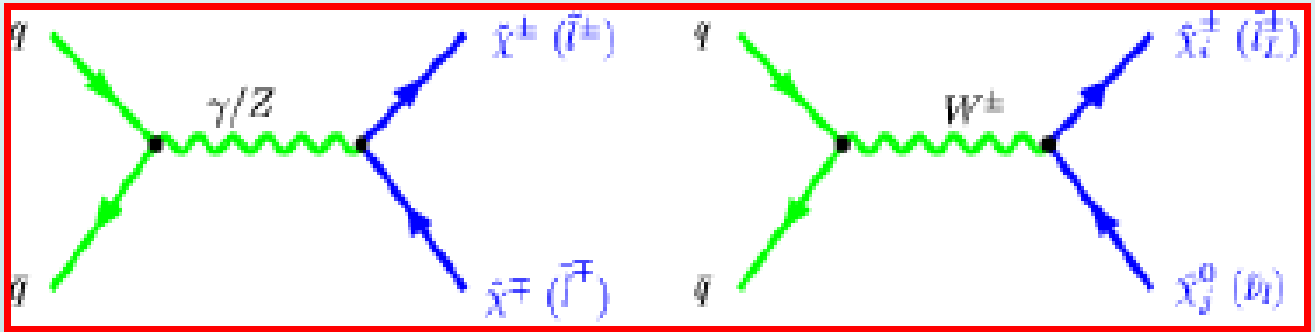
Higgs funnel

decay to fermion pair through resonant A exchange $\left(m_A \approx 2\,\tilde{\chi}_1^0\right)$ – high tanβ

Production mechanisms

Squark/Gluino Production

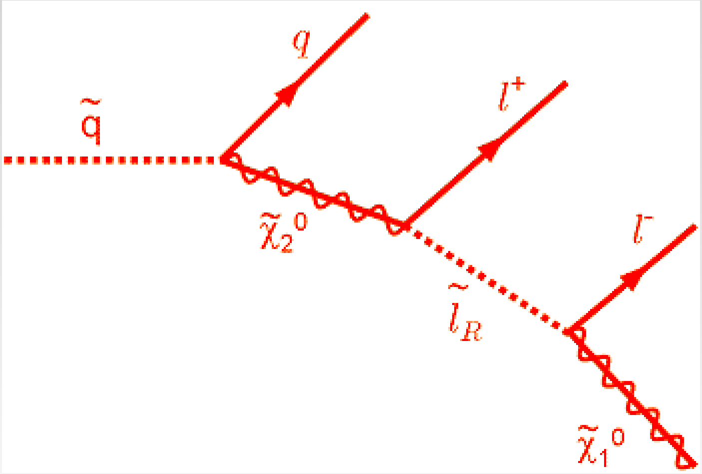


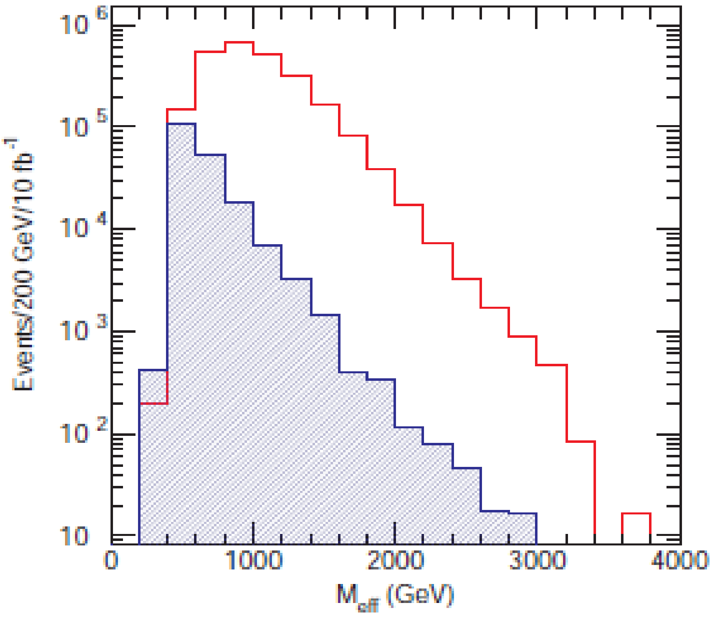


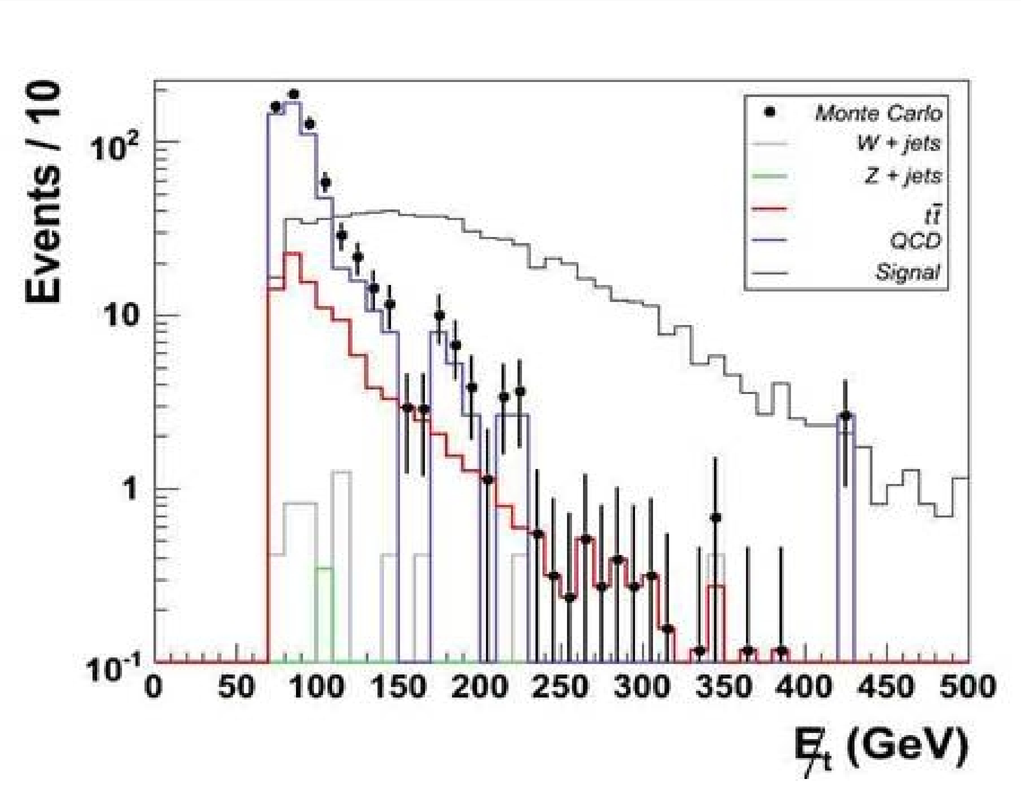
Direct Gaugino Production

Decay cascades

- Most SUSY channels involve several successive decays, until the LSP is reached.
- Signature of SUSY would be an excess in missing Et (or missing + visible Et)

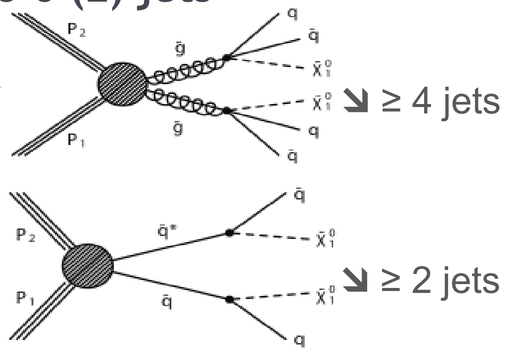






Strong Production with 0-lepton signature

- Searches in inclusive jets + *E*tmiss events
  - from 2 (A) to 6 (E) jets

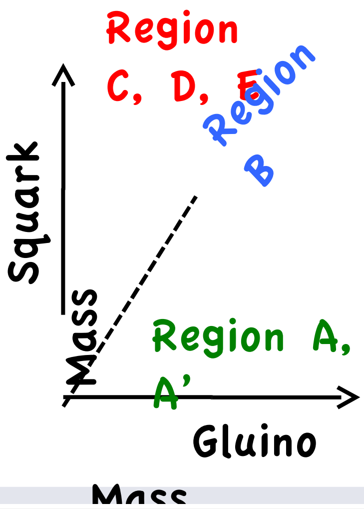


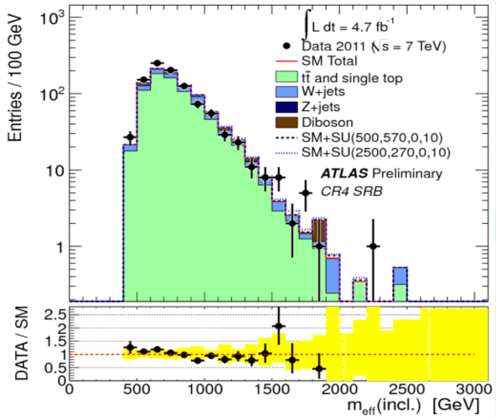
$\tilde{g} \rightarrow q\tilde{\chi}_1^0$

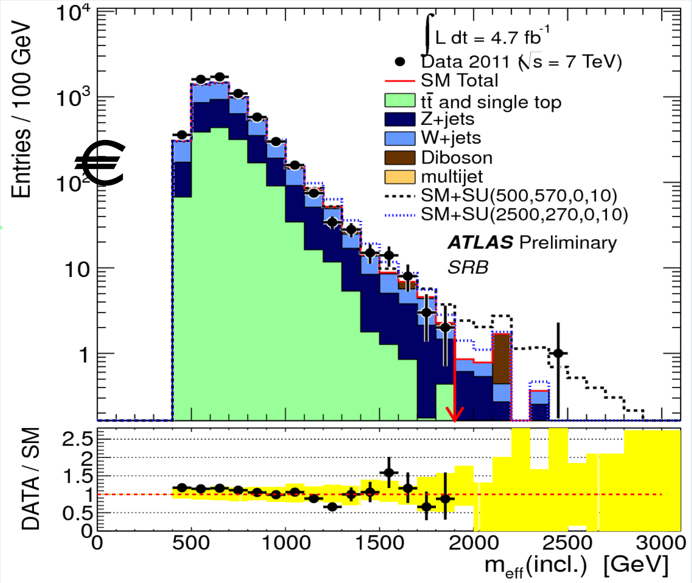
$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$

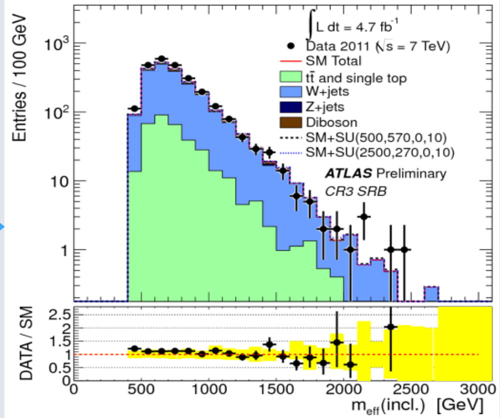
Expect significant ‘’effective mass’’

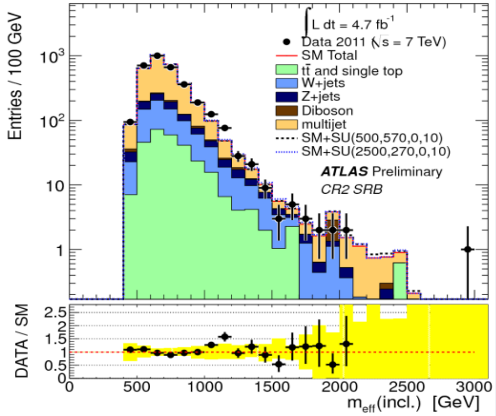
$$\sum_{\text{jet}} E_{T,\,\text{jet}} + E_T^{\text{miss}}$$

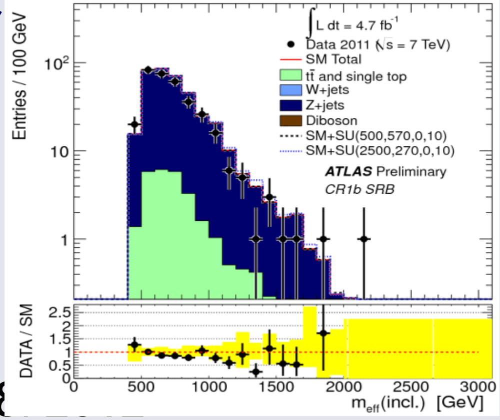






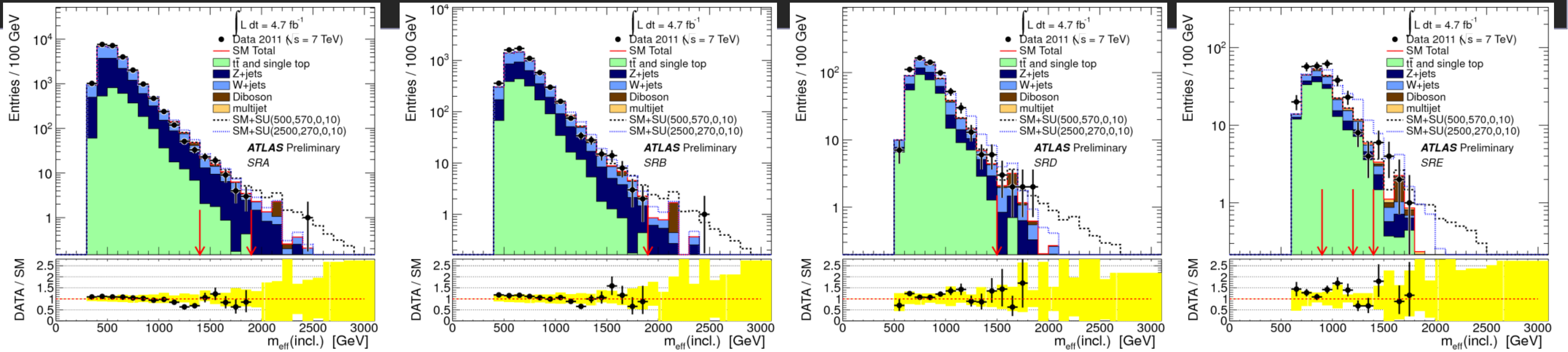




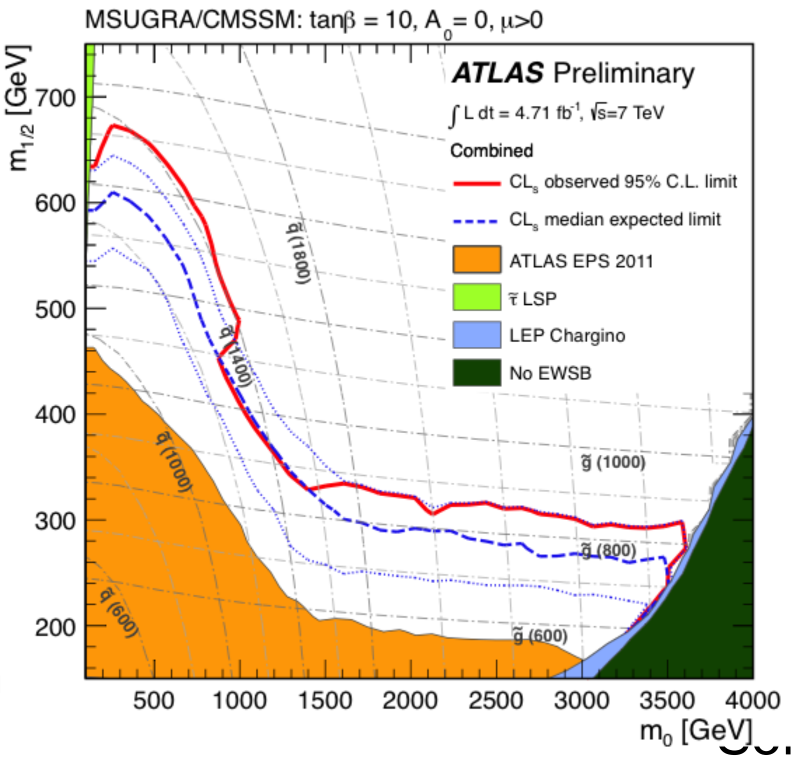


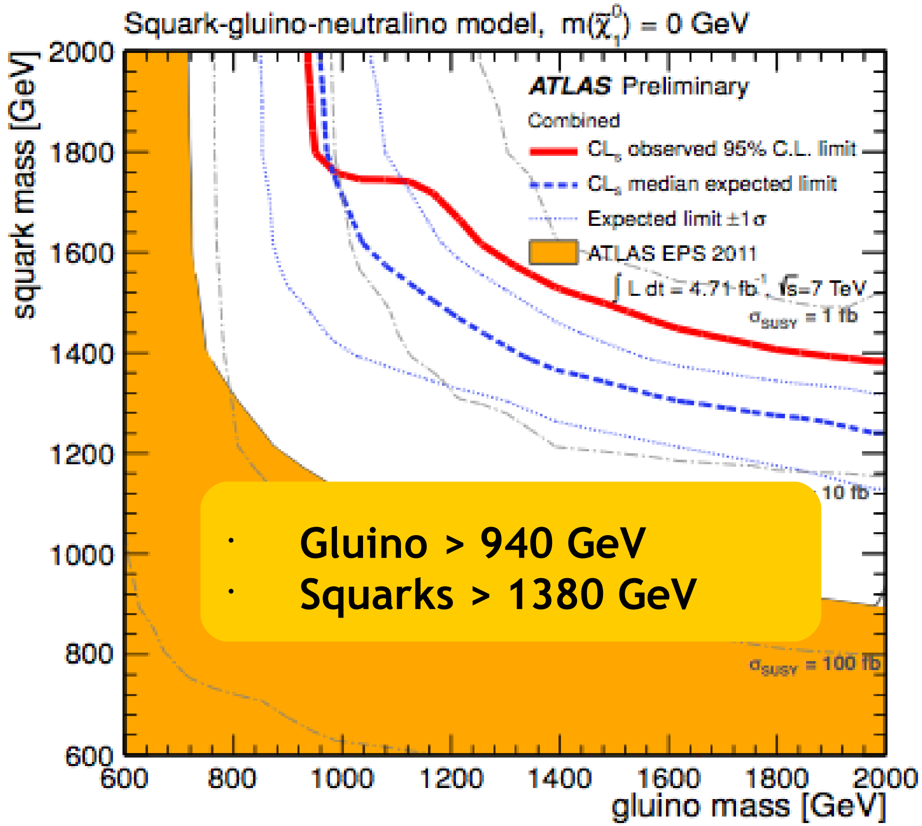
Normalizations obtained in all CR and extrapolated to signal regions simultaneously by combined maximum likelihood fit

Results of inclusive jets + *Etmiss*



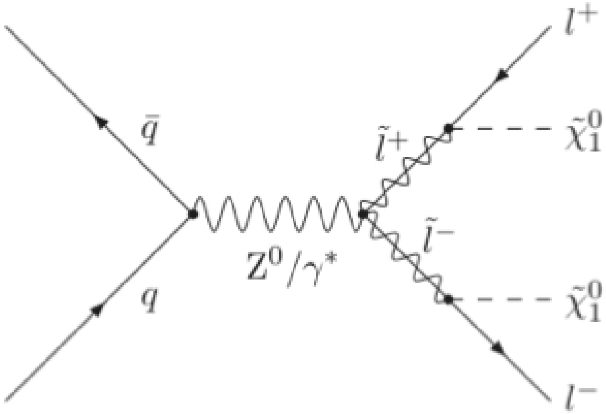
- Interpretation of the results in mSUGRA and phenomenological models

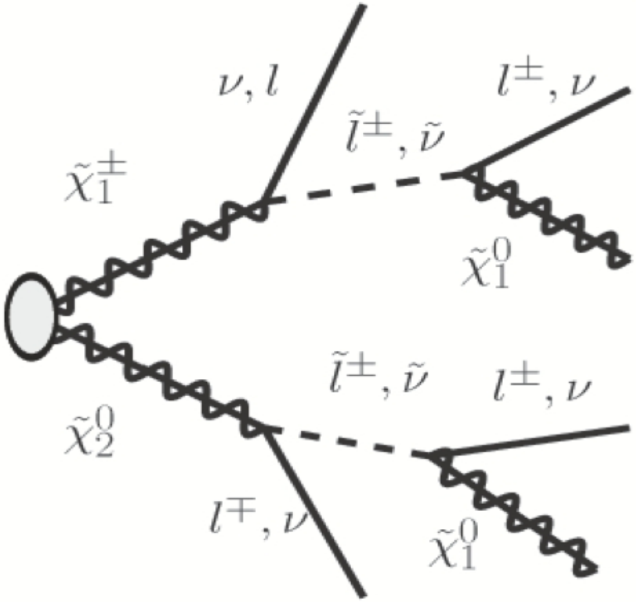




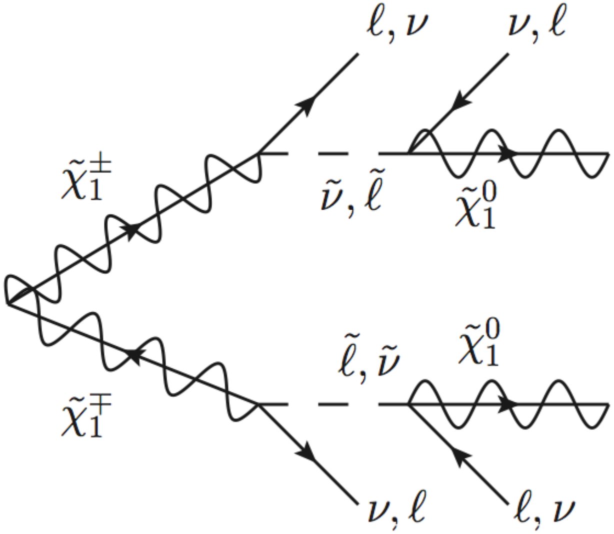
- **Gluino > 940 GeV**
- **Squarks > 1380 GeV**

Weak Production



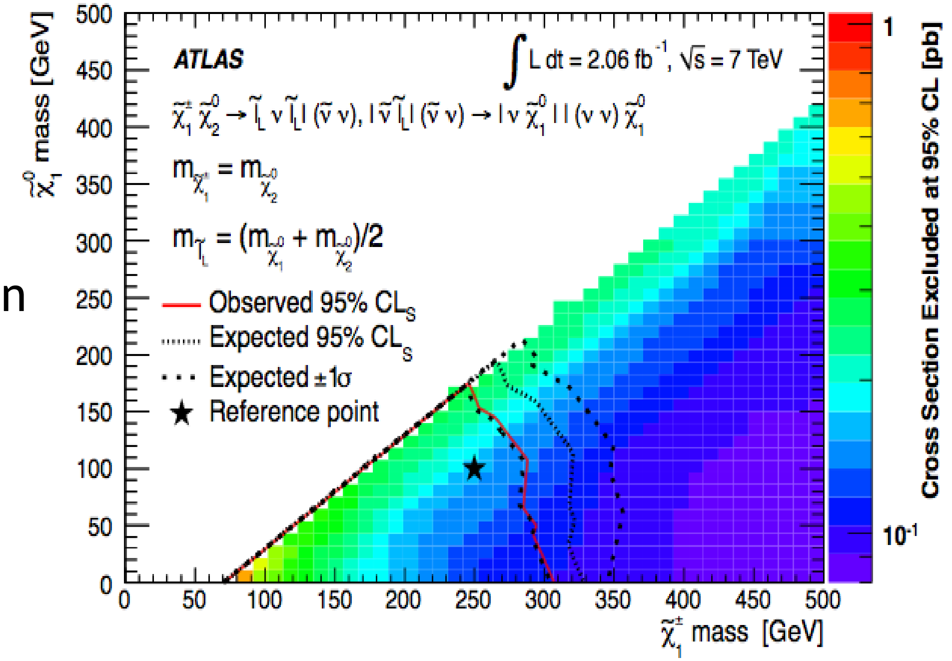


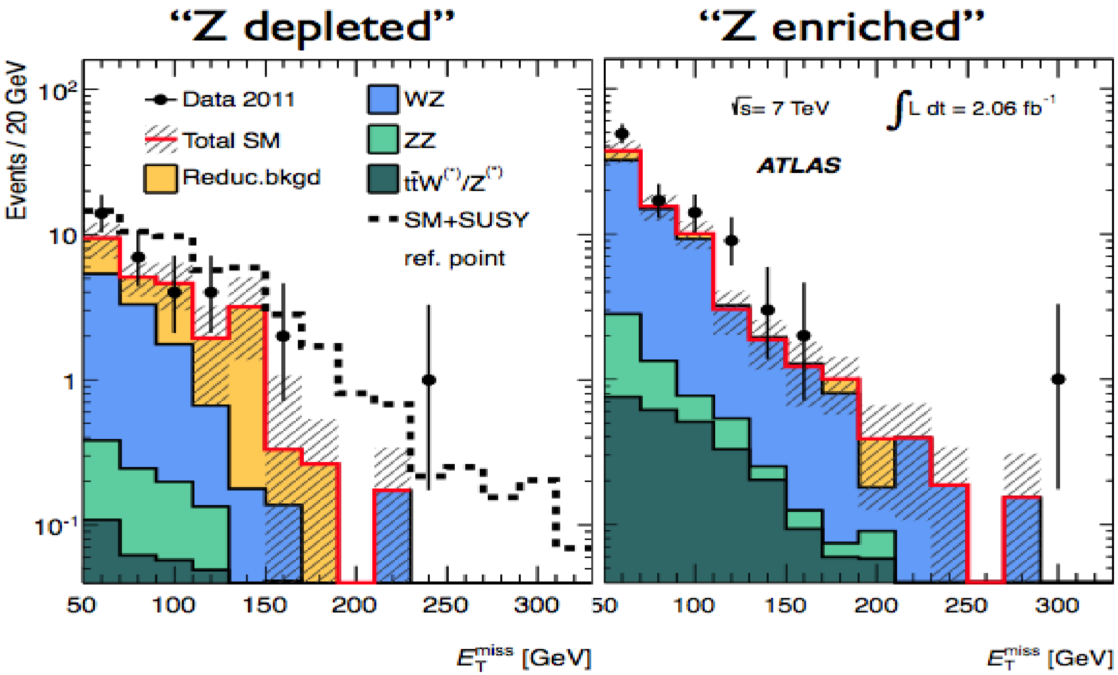
Decay	Number of identified leptons
	$\tilde{\chi}_2^0\tilde{\chi}_1^\pm$
$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to (\ell^+\ell^-\tilde{\chi}_1^0) + (\ell^\pm\nu\tilde{\chi}_1^0)$	3
$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to (\ell^+\ell^-\tilde{\chi}_1^0) + (\ell^\pm_{mis}\nu\tilde{\chi}_1^0)$	2
$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to (\ell^+\ell^-_{mis}\tilde{\chi}_1^0) + (\ell^\pm\nu\tilde{\chi}_1^0)$	2
$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to (\ell^+_{mis}\ell^-\tilde{\chi}_1^0) + (\ell^\pm\nu\tilde{\chi}_1^0)$	2
$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to (\ell^+\ell^-\tilde{\chi}_1^0) + (q\bar{q}'\tilde{\chi}_1^0)$	2
	$\tilde{\chi}_1^\mp\tilde{\chi}_1^\pm$
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm \to (\ell^\pm\nu\tilde{\chi}_1^0) + (\ell^\mp\nu\tilde{\chi}_1^0)$	2
	$\tilde{\chi}_2^0\tilde{\chi}_2^0$
$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to (\ell^\pm\ell^\mp\tilde{\chi}_1^0) + (\ell^\pm\ell^\mp\tilde{\chi}_1^0)$	4
$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to (\ell^\pm\ell^\mp\tilde{\chi}_1^0) + (qq\tilde{\chi}_1^0)$	2

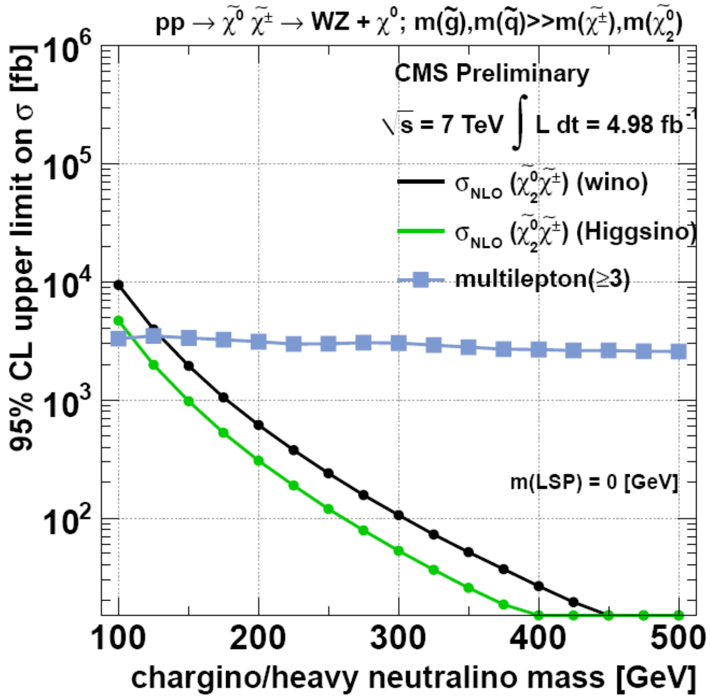


Direct Weak Gaugino

- Search for chargino and neutralino production in the **3-lepton and ETmiss final state**
    - Z-depleted SR (slepton mediated)
    - Z-enriched SR (Z mediated)
- Simplified Model and pMSSM

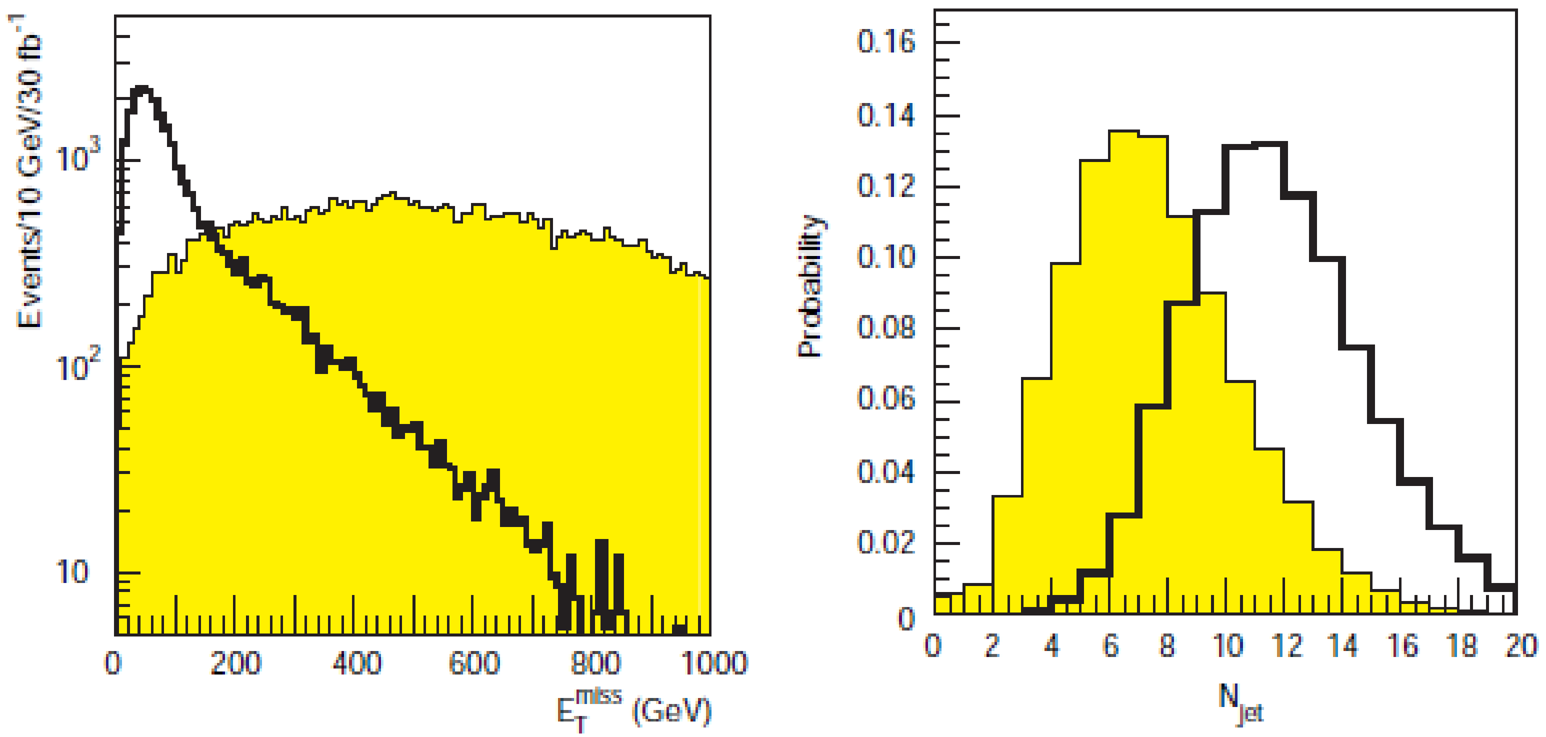






R-parity violating models

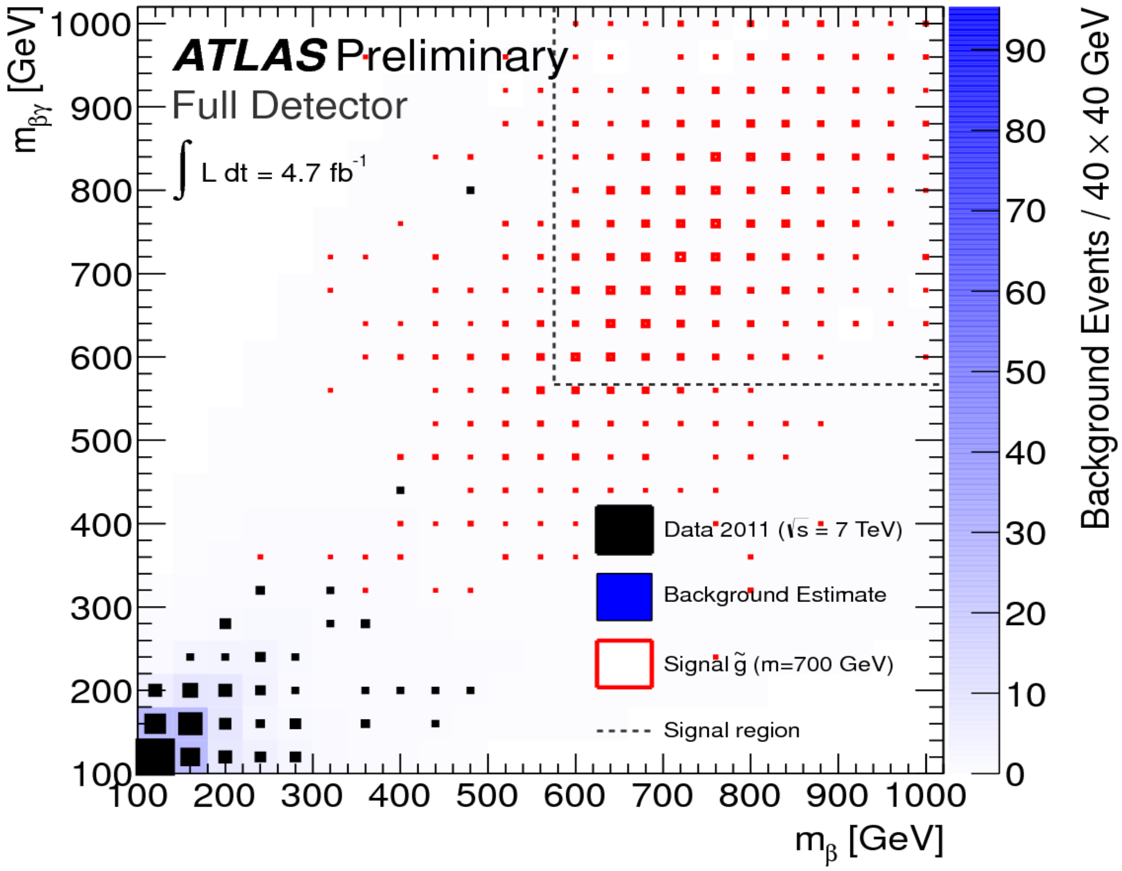
- If R is not conserved, SUSY particles can decay into SM ones, so events do not have the characteristic MET signature, but rather an anomalously high number of jets or leptons:

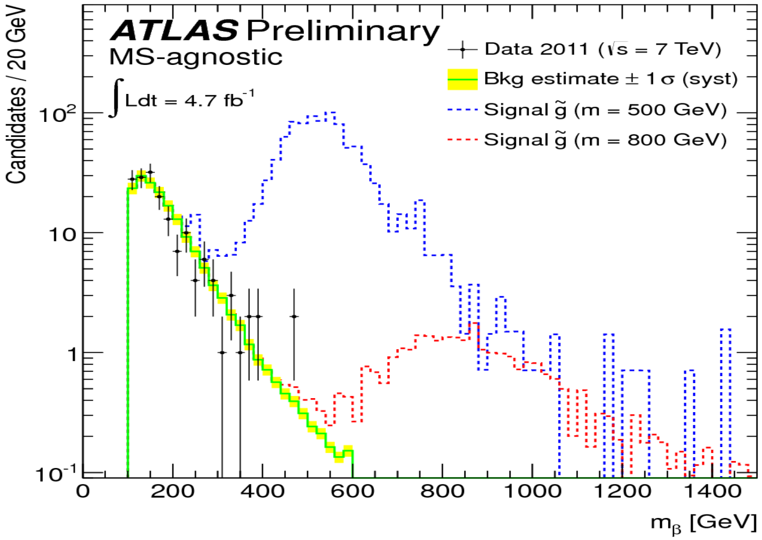


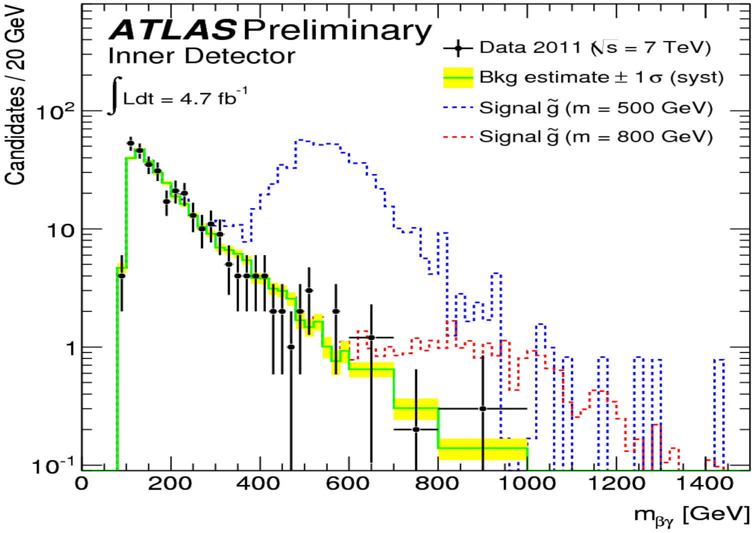
R-parity violating

R-parity conserving

R-hadron searches - results



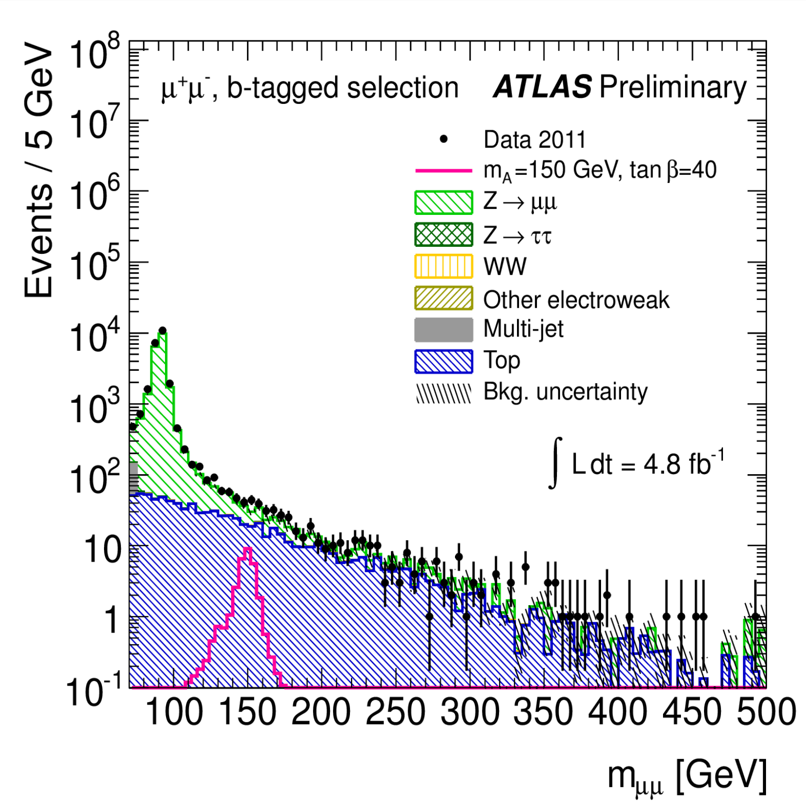


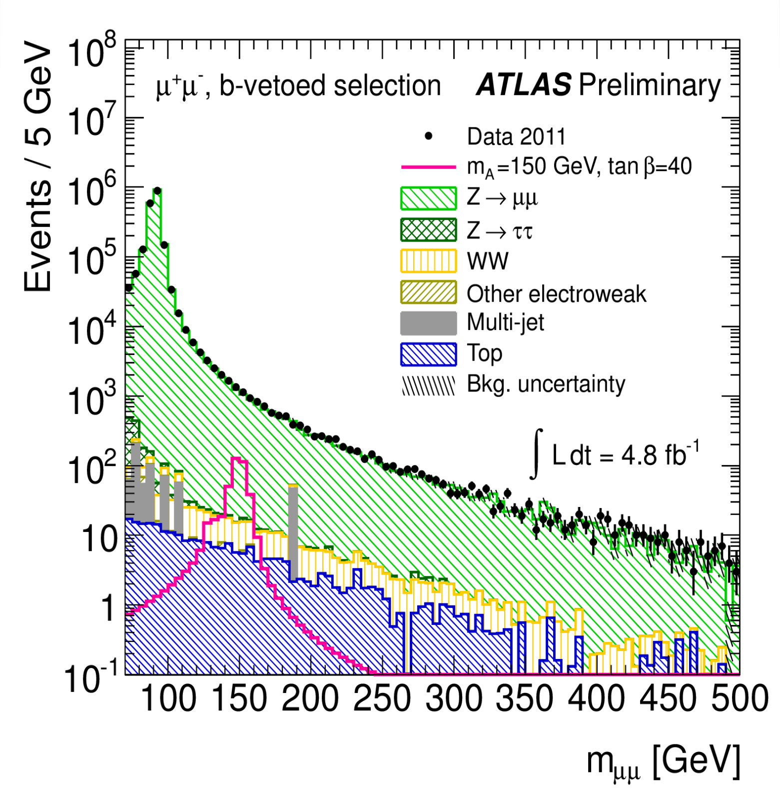


- ID-only: selection based on exceeding dE/dx thresholds

What about SUSY Higgs?

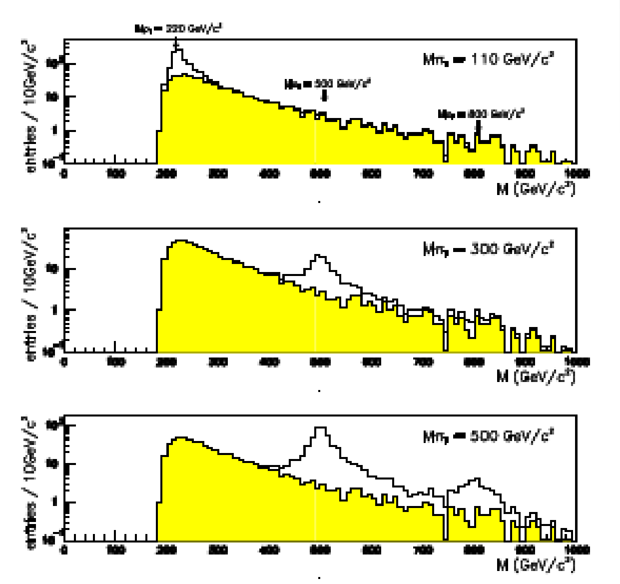
- In MSSM, 5 Higgs bosons: 2 charged (H+/-) three neutral h/A/H
- For some regions of SUSY parameter space, one of them may behave similarly to the SM one, so if the 125 GeV resonance is a SM-like Higgs, this does not rule out SUSY
- Nothing found on dedicated h/A/H searches in lepton pairs + jets



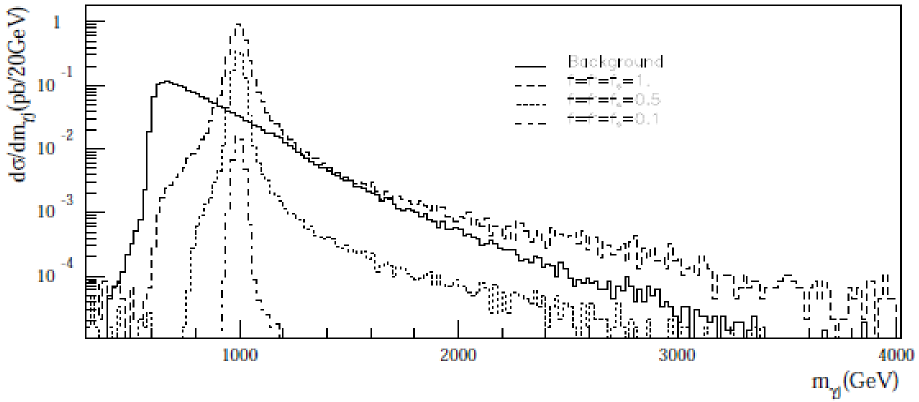


Other new physics models

- Technicolour: an additional interaction modeled after QCD colour simmetry replaces the Higgs mechanism to give mass to the other particles. Predicts unobserved FCNC but some variants compatible with experimental data. Signature are resonances decaying into W and Z, like rho decays into pions

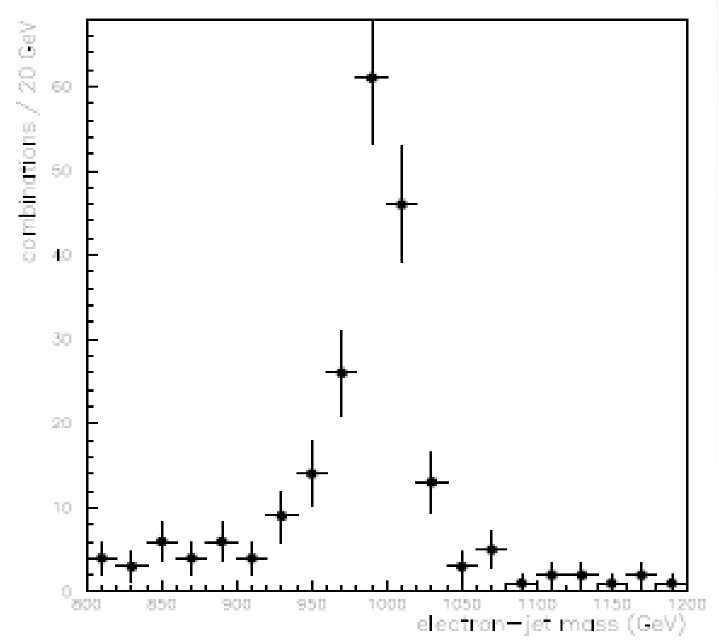


•Excited quarks/leptons: decay into a photon and a quark/lepton, producing a mass peak in that distribution

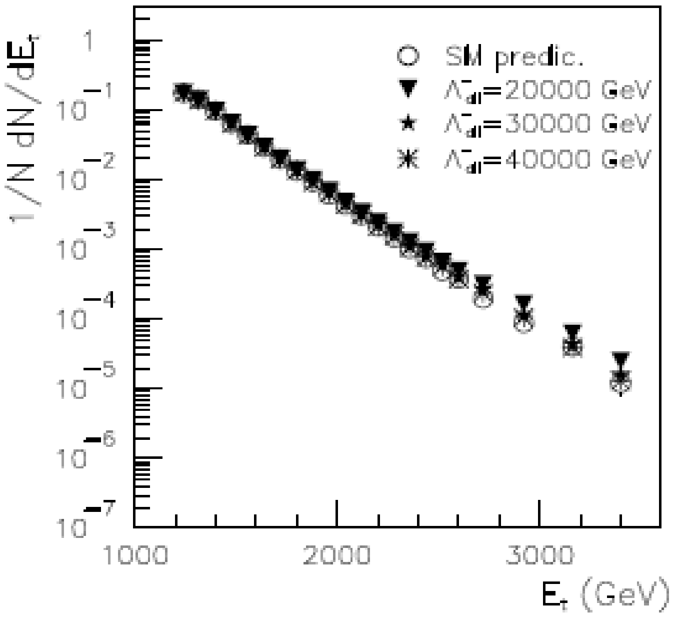


More new physics

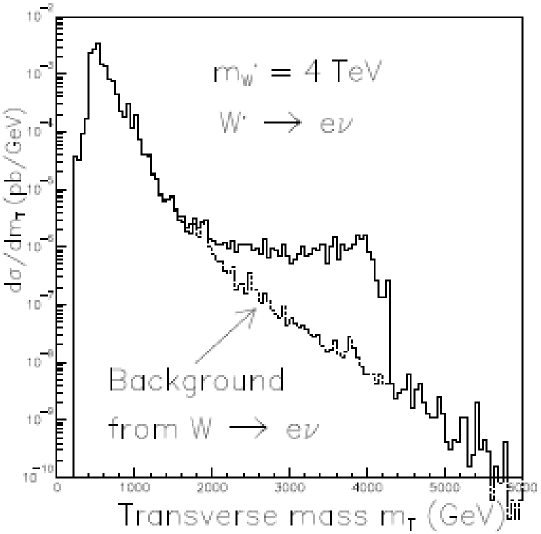
- Leptoquarks: a new symmetry between leptons and quarks could produce particles strongly coupling (and decaying) to both



Compositeness: if quarks are composed of something even smaller, that would result in increased high-mass dijet tail

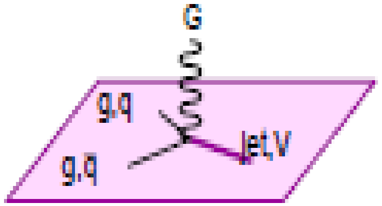


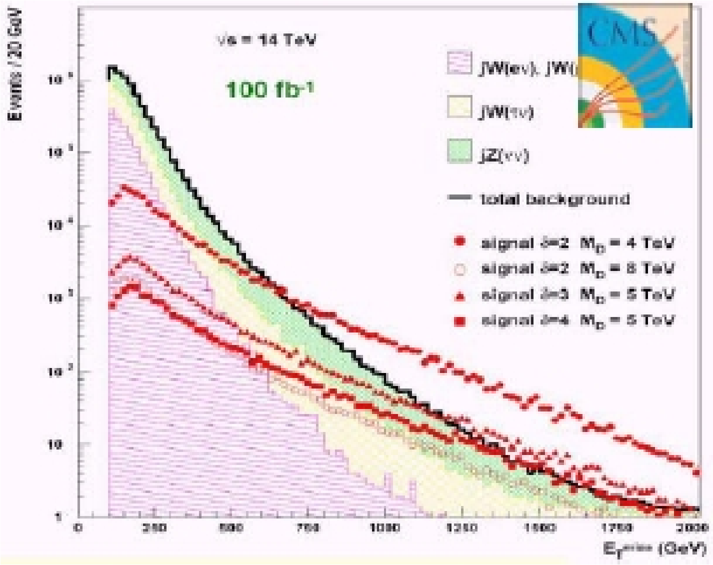
Z', W': from additional SU(2) symmetry, behave like high-mass W's and Z's

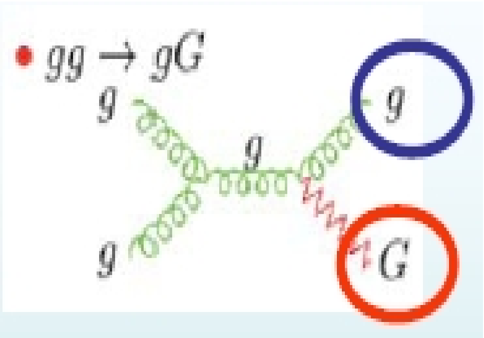


Extra dimensions

- The three space dimensions we live in are just a membrane of a multi-dimensional space.
- This would reduce the hierarchy problem to geometry
- Gravity could deviate from Newton's law at small scale (< 1 mm, very few experiments on that), and could propagate to the extra dimensions; a graviton would disappear from our universe and be seen as missing energy

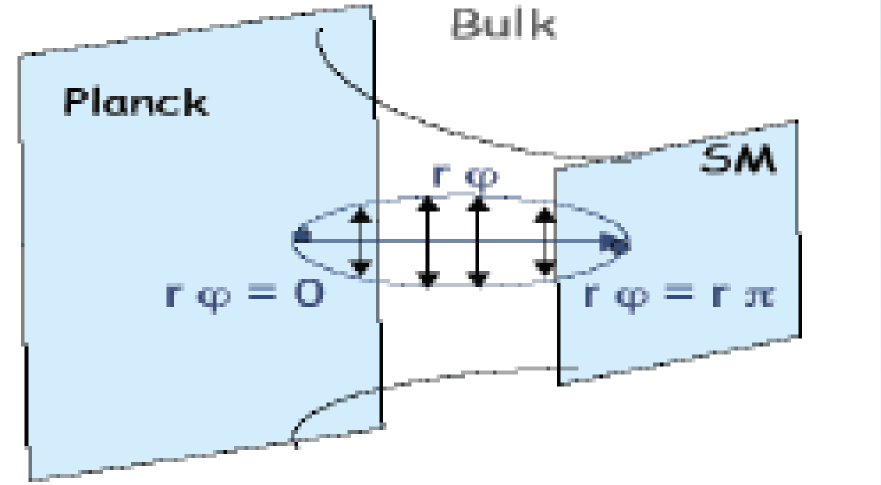






Great way to escape from the in-laws???

Randall-Sundrum models

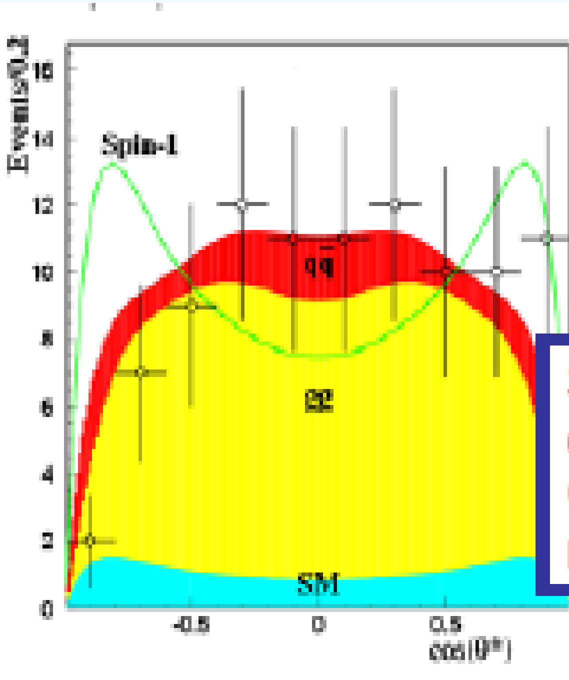


A small, highly curved ("warped") extra dimension connects the SM brane (at O(TeV)) to the Planck scale brane

Gravity small in our space because warped dimension decreases exponentially between the two branes

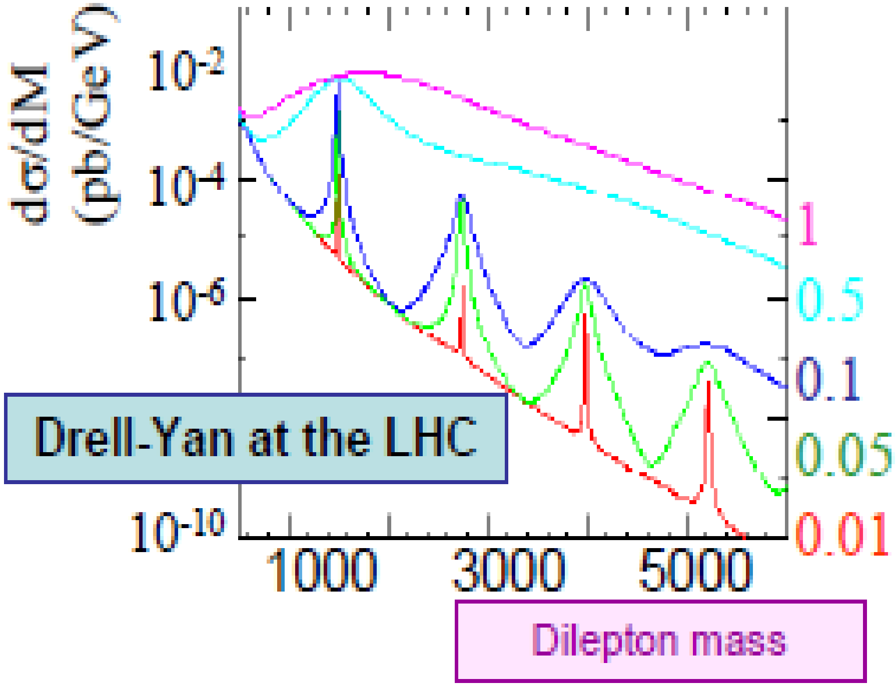
Series of narrow, high-mass resonances:
(only first peak visible at LHC, due to PDFs)

$$q\bar{q}, gg \to G_{KK} \to \ell^+\ell^-, \gamma\gamma, j+j$$

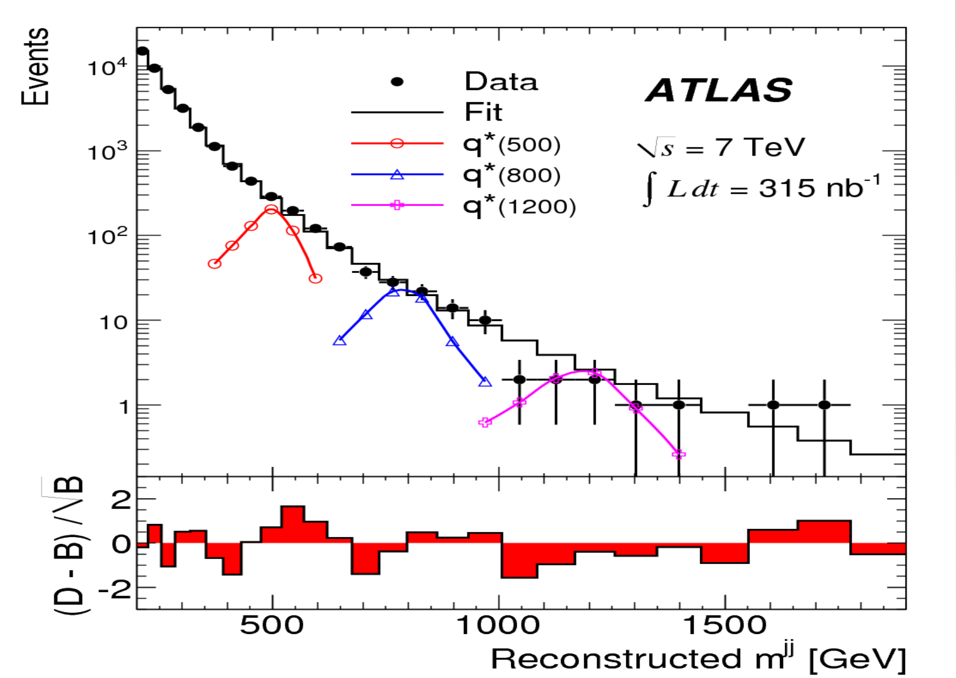


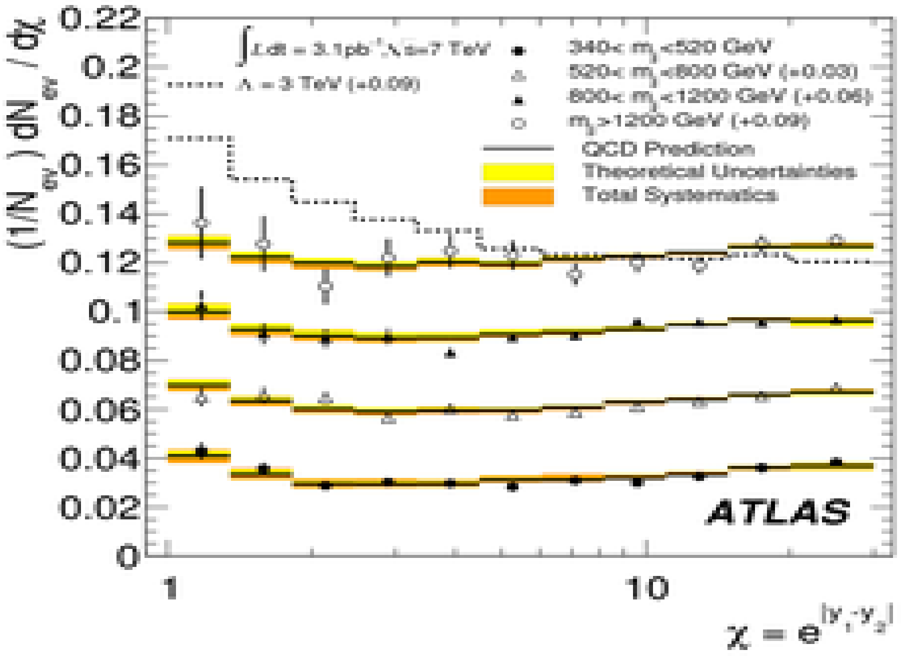
Spin analysis to distinguish spin-2 G from spin-1 Z' resonance

Antonella De



Exotic seaches with dijets





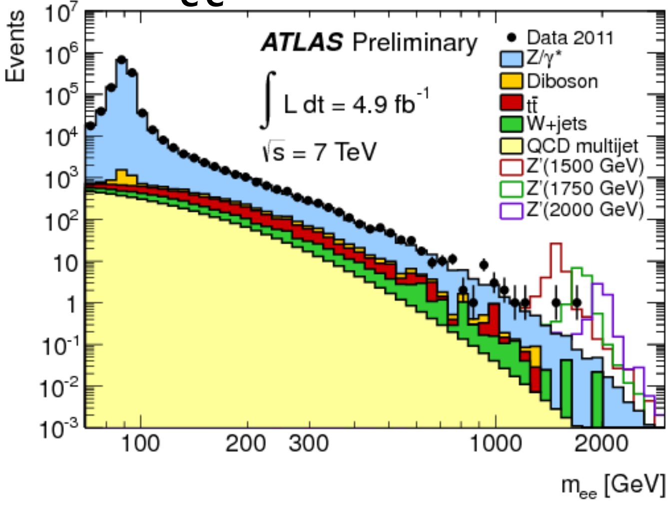
- Technicolor, colour interaction and low-mass gragvity models all predict productin of resonances, mainly decaying into dijets. Dijet distributions can be interpreted in the framework of new physics search

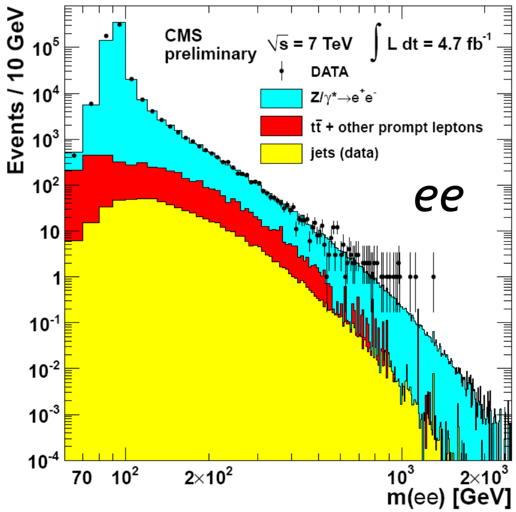
Di-lepton resonances

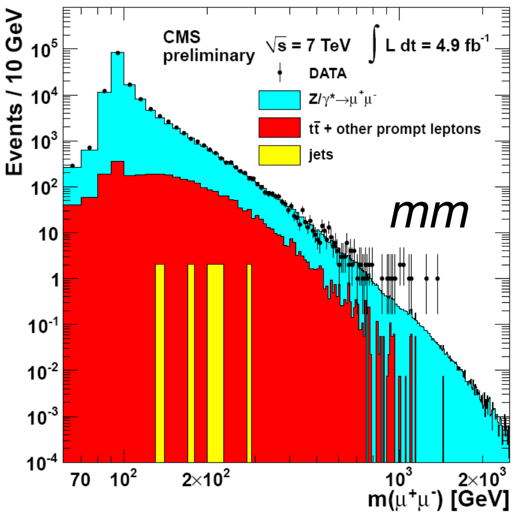
Constrain Z’ and RS graviton (G*) production in e+e- and m+m- invariant mass distributions

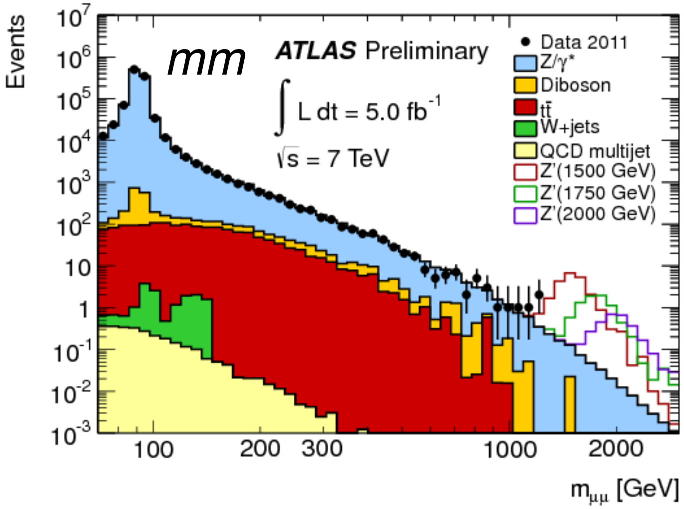
- Search also in for tt final states for t(e)t(m), t(e)t(h), t(m)t(h), t(h)t(h)

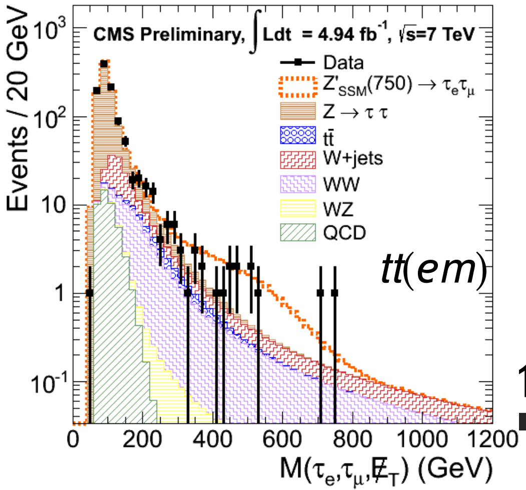
ee









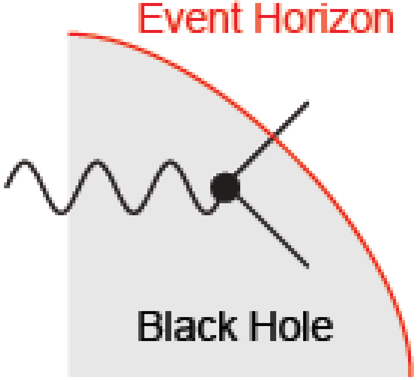


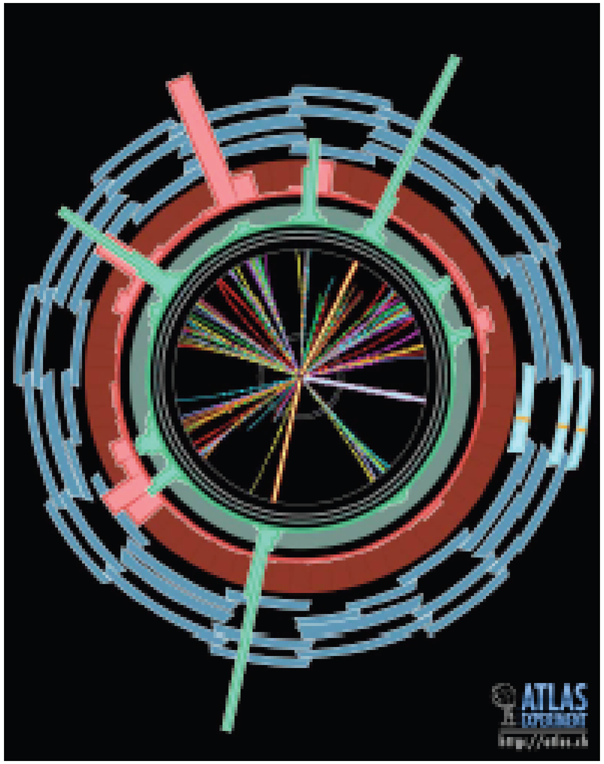
Black hole phenomenology

- BH decay:
  - BH loses energy by Hawking radiation: pair production close to event horizon → one particle tunnels through horizon
  - BH lifetime for M_D = 1 TeV:

$$\tau \sim \frac{M_{\mathrm{BH}}^{(n+3)/(n+1)}}{M_D^{2(n+2)/(n+1)}} \approx 10^{-26}\ \mathrm{s}$$

  - "Democratic" thermal decay (obeying all conservation laws): equal fractions of all SM particles
  - Spectacular signature: spherical high-multiplicity events ("hard to be missed")



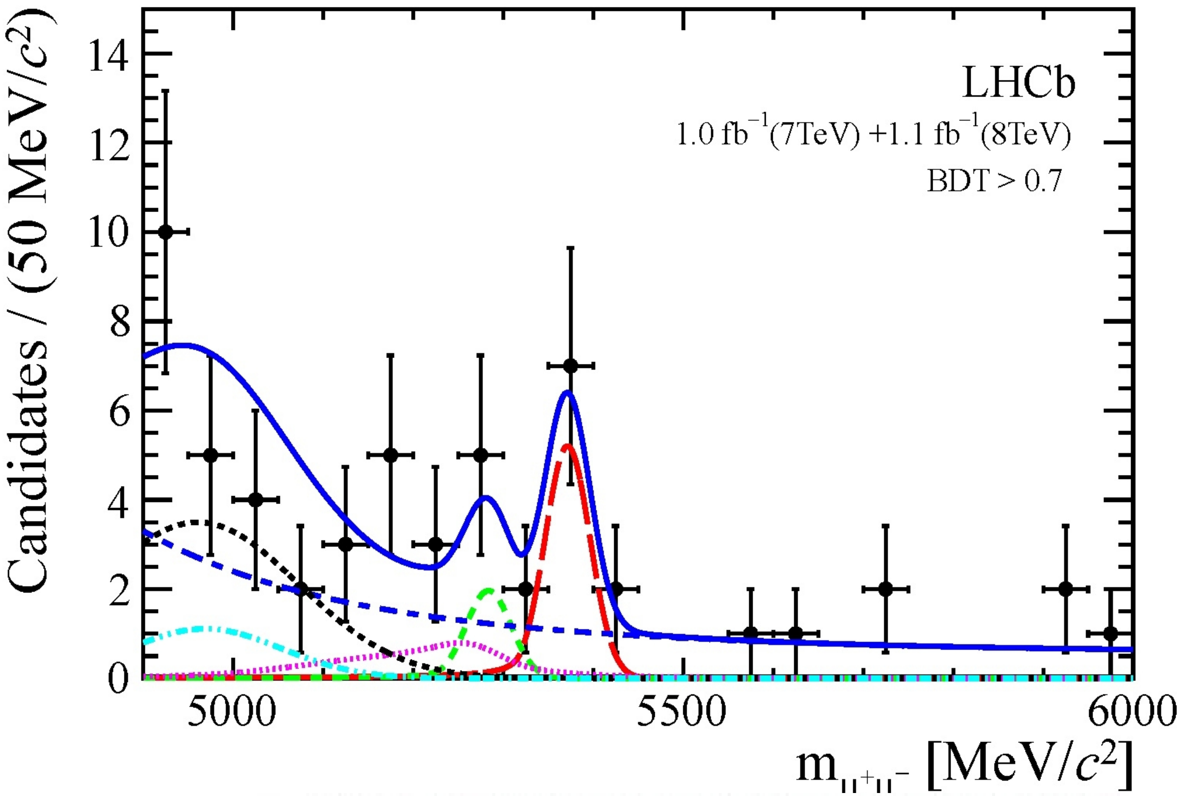


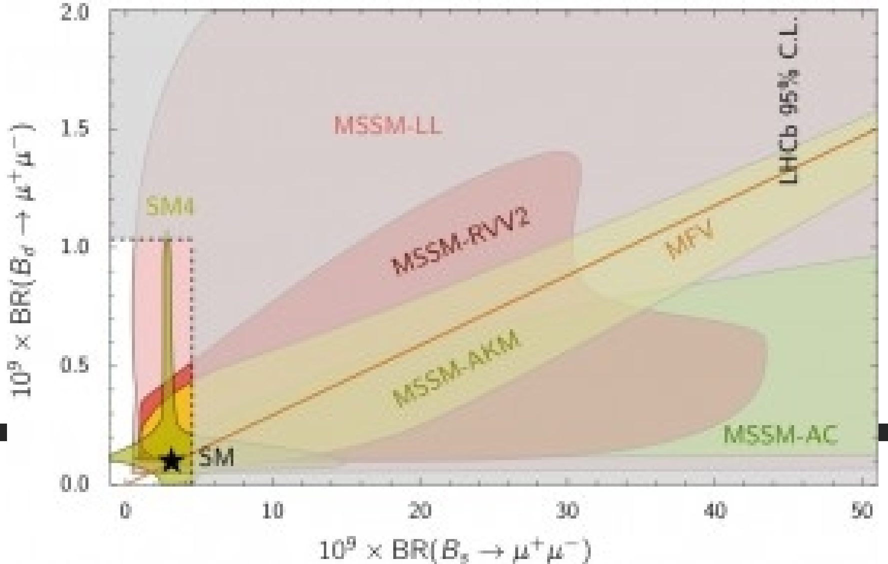
[atlas.ch]

Search summary table (theory)

[Hitoshi Murayama]

What does B-physics say?





Some rare decays like Bs->μμ only occur through loop diagrams.
If new particles exist, they can also be produced in these loops, leading to big modifications of the SM branching fractions.

B-physics, not covered in these lectures, is a powerful tool to get indications and limits on the existance of new particles with masses much higher than those directly accessible at the LHC

After all, both the top and the Higgs masses have been predicted with good precision before discovery, using virtual loop techniques

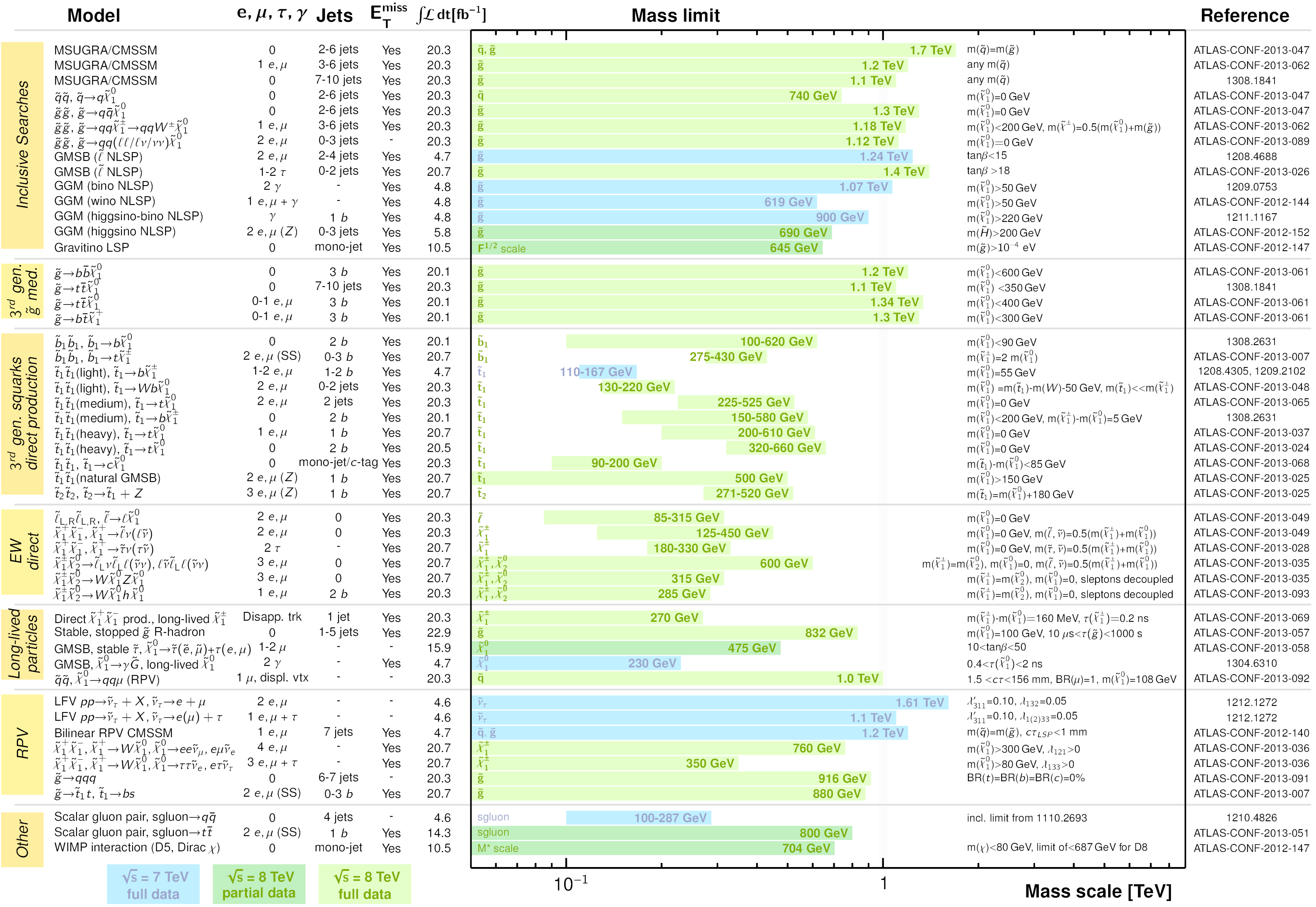
The bad news is that in this case no deviation from SM behaviour is in sight

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

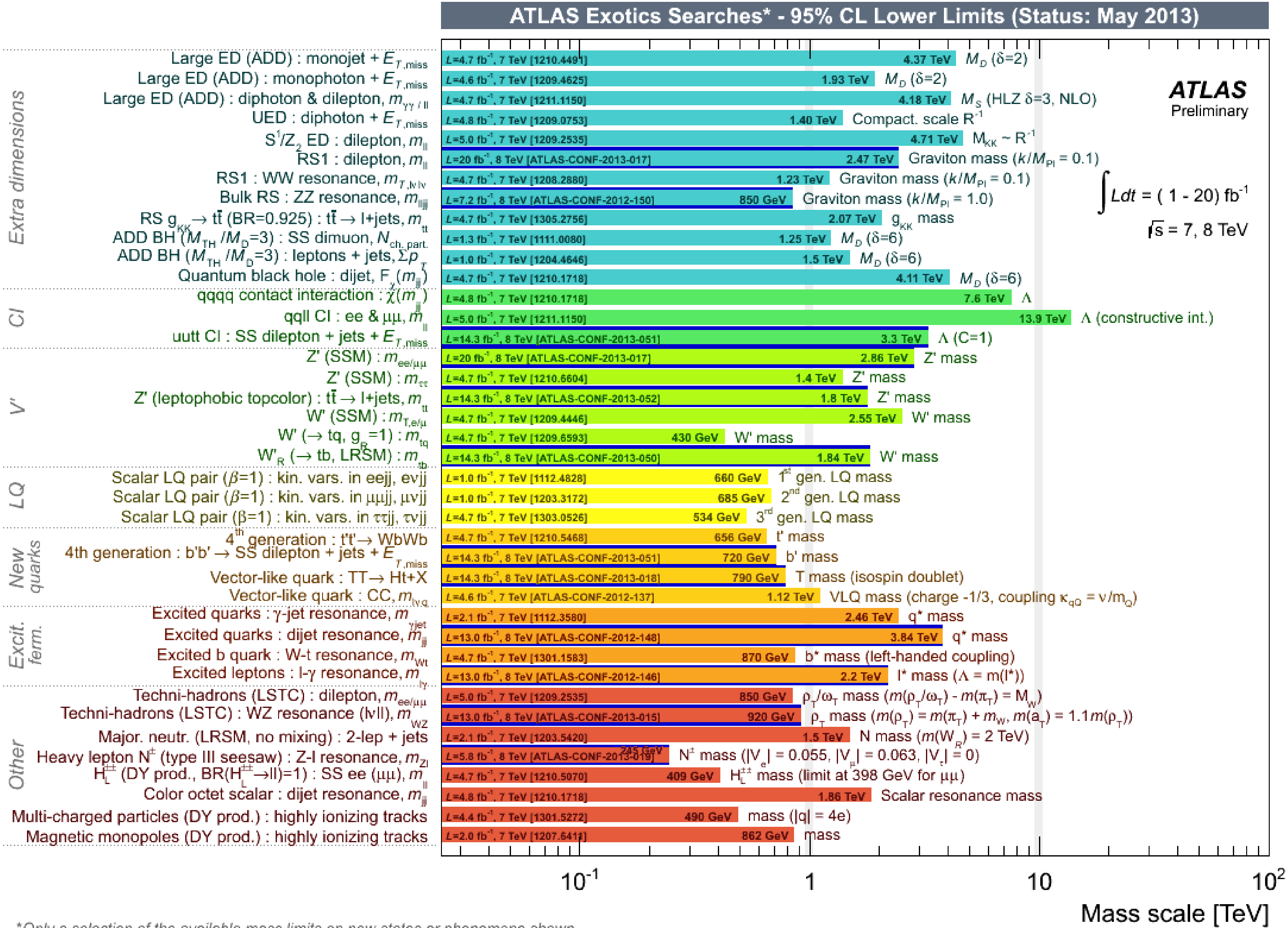
ATLAS Preliminary

$\int \mathcal{L}\, dt = (4.6 - 22.9)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV



	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	740 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$)	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20.3	$\tilde{g}$	1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\tau}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$	1.4 TeV	tanβ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	4.8	$\tilde{g}$	1.07 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	$\tilde{g}$	619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	$m(\tilde{g})>10^{-4}$ eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.2 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2013-061
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$	275-430 GeV	$m(\tilde{\chi}_1^\pm)$=2 $m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$	110-167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	130-220 GeV	$m(\tilde{\chi}_1^0)$ =$m(\tilde{t}_1)$-$m(W)$-50 GeV, $m(\tilde{t}_1)$<<$m(\tilde{\chi}_1^\pm)$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	$\tilde{t}_1$	225-525 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20.7	$\tilde{t}_1$	200-610 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$	320-660 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-200 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$	500 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$	271-520 GeV	$m(\tilde{t}_1)$=$m(\tilde{\chi}_1^0)$+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$	85-315 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$	125-450 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell}, \tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	180-330 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau}, \tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_{\mathrm{L}}\nu\tilde{\ell}_{\mathrm{L}}\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_{\mathrm{L}}\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	600 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell}, \tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	315 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e, μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	285 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$	270 GeV	$m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$	832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$	1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e + \mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e(\mu) + \tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e, μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$	1.2 TeV	$m(\tilde{q})$=$m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	760 GeV	$m(\tilde{\chi}_1^0)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.7	$\tilde{\chi}_1^\pm$	350 GeV	$m(\tilde{\chi}_1^0)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$	880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e, μ (SS)	1 b	Yes	14.3	sgluon	800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.



*Only a selection of the available mass limits on new states or phenomena shown

Conclusions

- As you saw, the physics program of the LHC is huge (only gave a few snapshots), and even if legions of physicists will analyse the data, there is really a lot to be occupied over many years
- Detector understanding and calibration is crucial; first data taking period was used to understand detectors and re-discover the SM, and study some missing details
- Many measurements already performed on jets, W, top physics
- Searching for the SM Higgs, a new boson has been discovered by both experiments for mass values around 125 GeV.
- All properties of this new resonance consistent with a SM Higgs
- Existence confirmed in the ZZ* channel, as well as injected signal in WW (but no mass determination there)
- The SM has never been stronger